FUEL SAVINGS OPPORTUNITIES FROM AIR REFUELING

THESIS

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Abstract

Fuel is a critical strategic asset for military aviation operations, yet is increasingly expensive. Air refueling offers both the opportunity to extend aircraft range and the potential to save fuel by enabling a transport aircraft to depart with less fuel in exchange for additional cargo. We evaluate the practicality of air refueling in terms of fuel savings versus distance and cargo quantity, by introducing two non-linear optimization models that examine the tradeoff between departure fuel weight and loaded cargo for given origin, destination, and tanker base positions and freight quantities to be moved. We use various numerical example scenarios to show that substantial fuel savings from air refueling are possible.

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This thesis is dedicated to my beloved wife. Her faithful encouragement, unyielding belief in my ability to excel, patience, love and wonderful cooking were all crucial to my being able to complete this intense program.

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Murat Toydas

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1. Introduction

1.1. Motivation

The United States of America is one of the largest fuel consumer countries in the world. It consumes over 24% of total world oil production (Davis et al, 2007). Moreover, its fuel consumption has an ascending trend (See Table 1-1). Additionally, the U.S. is highly dependent on foreign countries for fuel. It imported 59.6% of its total consumption in 2006 and the import trend is also parallel to the consumption trend (Davis et al, 2007). Greene et al (2007) indicate that the oil market upheavals caused by the OPEC cartel over the last 30 years have cost the U.S. in the vicinity of $7 trillion (present value 1998 dollars) in total economic costs, which is about as large as the sum total of payments on the national debt over the same period. Thus, it is clear that fuel is a very important and scarce resource for the U.S.

Table 1-1. The U.S. Petroleum Consumption & Imports

Year	Consumption*	Total Imports*
1960	9.80	1.82
1970	11.7	3.42
1980	17.06	6.91
1990	16.99	8.02
2000	19.7	11.46
2006	20.59	13.61
* Million Barrel Per Day		

Furthermore, JP-8 jet fuel is a necessary strategic asset for effective United States Air Force (USAF) operations now and for the foreseeable future. The USAF has a regular

and significant demand for fuel, and alternative fuels are not yet feasible or available in sufficient quantity to be used as a significant substitute. The U.S Air Force alone consumed 2.2 billion gallons of aviation fuel in 2007, costing $5.87 billion (Saglam, 2009). Hence, the USAF set a goal to reduce fuel consumption by 10% by 2016 without diminishing mission capability and effectiveness. If this objective is attained, $770 million can be saved annually. To achieve its goal, the USAF is attacking the issue with the following initiatives:

a) Fuel Conservation Culture
b) Mission and Training Validation
c) Flying Training Migration to Simulators
d) Air Refueling Optimization
e) Weight Reduction
f) Fuel Efficient Ground Operations
g) Demand Side Fuel Accountability
h) Direct Routing and
i) Alternative Energy Resources

Not surprisingly, a couple of the initiatives are related to operational procedures. As Hopkins et al (1977) note, changes to operational procedures offer an immediate and inexpensive method to conserve fuel and should be implemented on a priority basis.

1.2. Setting and Problem Statement

Air refueling seems to have potential for two of the initiatives, "Air Refueling Optimization" and "Weight Reduction". But the USAF generally considers air refueling as a flexibility mechanism. Operationally, it extends the range of fighter and cargo

aircraft and provides additional payload and loiter time for combat and combat support forces, allowing fighters and bombers to attack targets deeper in enemy territory and/or with greater payloads (Camerer, 2001). For example, Navy fighter aircraft taking off from an aircraft carrier use air refueling to allow takeoffs with a full weapon load and overcome the short runway constraint. Additionally, the North Atlantic Treaty Organization (NATO) looks at air refueling as a way of spatial or temporal extension of other air capabilities like strike or transport (Future of Air-to Air Refueling in NATO, 2007).

Visser (2001) studied possible effects of air refueling for commercial aircraft. He comments that "air refueling could include more specific goals, such as reducing takeoff weight to increase takeoff and climb out performance while still maintaining the required range. A reduction in takeoff weight would also help noise issues".

Air refueling is always a significant option for cargo aircraft to accomplish missions beyond their unrefueled range. If the distance flown is within range, then air refueling is not generally considered. However, air refueling has a potential to save fuel for such within-range missions. Increasing aircraft payloads can reduce the total number of cargo aircraft sorties flown for a given lift requirement, which may lead to fuel savings depending on certain tradeoffs, which are now discussed.

Maximum takeoff weight limits and distance between origin and destination are two important factors that affect both initial fuel and loaded freight. Additionally, a tradeoff exists between initial fuel and loaded freight because of maximum takeoff weight and aircraft capacity constraints. For a given distance within unrefueled range, as more fuel is loaded, less freight can be moved. Potentially, fewer cargo aircraft sorties are

needed to move a certain amount of freight. In this situation, the tradeoff is between the fuel saved by cutting cargo aircraft sorties and the additional fuel used by the tanker aircraft.

This directly leads to the question: “in terms of fuel consumption, is within-range air refueling a feasible and efficient operational approach for single/multiple transport aircraft departing from the same location and heading to the same destination?”

1.3. Research Objectives

The fundamental objective of this research is to advance a mathematical model that examines two key tradeoffs. The first tradeoff is between initial fuel and freight loaded to cargo aircraft for a given origin, destination and freight weight to be moved. The second tradeoff is between fuel saved by cutting cargo aircraft sorties versus the additional tanker aircraft fuel consumption for the same inputs and a given tanker base location. Then, the feasibility and efficiency of using air refueling can be evaluated in terms of total fuel consumption. An appropriate model can provide an easy-to-use quick-look decision tool, which can allow decision makers to plan more fuel efficient air transportation missions.

A second objective of this study is to provide a proof of concept for the model by applying the model to several plausible lift scenarios. To achieve these objectives, the following sub questions will be answered in the study:

- What are the fuel usage functions for both cargo and tanker aircraft?
- What is the optimum air refueling point, number of cargo and tanker aircraft, initial cargo and fuel amount of each cargo aircraft to minimize total fuel consumption for a given origin, destination, tanker base location and cargo movement requirement?

- What is the total fuel consumption for both “with air refueling” and “without air refueling” options for a given a given origin, destination, tanker base location and cargo movement requirement?
- What is the refueling breakeven point for the cargo movement requirement for a given origin, destination, and tanker base location?

1.4. Scope

The scope of this research is to build and test a mathematical model that captures the tradeoffs introduced in Section 1.3. The focus of this study is on USAF C-5 and C-17 cargo aircraft and KC-10 and KC-135 tankers. This study assumes tanker and cargo aircraft scheduling is perfect. Receiver or tanker aircraft are never late to a scheduled air refueling event. For routing, aircraft follow great circle distances which are the shortest distance between two points on the globe. Additionally, aircraft availability and ground support are unconstraining. The tanker base always has available tanker aircraft to execute this mission and there is no ground operation limitation such as physical space availability, etc. Finally, this study ignores factors that can prevent the execution of air refueling such as tanker and/or cargo aircraft failure during air refueling, bad weather conditions at rendezvous point, etc.

1.5. Implications

This research can be used immediately in the USAF heavy transport community to help planners make decisions about air transportation missions—in particular, for assessing fuel usage for rapid deployment scenarios. Further, it can be used as a supplementary mission planning tool to the Computer Flight Planning Software/System

(CFPS) and Advanced Computer Flight Planning System (ACFP) currently used by the USAF to plan aircraft missions and calculate flight fuel requirements. These efforts will hopefully help to find more efficient uses of limited resources.

1.6. Preview

The remainder of this document is organized as follows: Chapter 2 provides a background and review of relevant literature. Chapter 3 is a stand-alone article manuscript to be submitted for publication consideration, that captures the principal contributions of this research. It provides an overview of pertinent literature about the research question. It follows with a development of the mathematical model which captures the cargo, fuel, and distance tradeoffs noted in Chapter 1. An application of the model on two broad overview scenarios is then demonstrated, followed by a conclusion and recommendations for further research. Chapter 4 provides an illustrative example of the model's application involving an Interim Brigade Combat Team (IBCT) deployment under different origin-destination scenarios. Chapter 4 concludes with a discussion of model limitations and recommendations for further studies.

2. Background

Researchers are pursuing three fundamental areas to reduce aircraft fuel consumption, including: 1) designing new fuel efficient aircraft and engines and modifying current aircraft; 2) developing alternative fuels; and 3) designing fuel efficient operational procedures. “The challenge of advancing aircraft design has been a continual process in man’s mastery of the air. Engineers have had to face a steady parade of tradeoffs in designing aircraft, primarily in the effort to have lift overcome drag with ever-increasing efficiency” (Ethell, 1983). New fuel efficient state-of-art fuselage styles, propeller and engines, composite structures, and alternative fuels such as synthetic fuels, bio-fuels, hydrogen, etc., are some of examples of design-side efforts. The purpose of finding new fuel efficient technologies is not only to build new aircraft models but also to equip current aircraft types with these fuel efficient technologies. “The application of advanced technologies shows the potential for significant improvement in fuel efficiency” (Lange ;1986)

Without modifying the aircraft, “airplane fuel efficiency can be increased in the short term by operational changes” (Pilati; 1974). Hopkins et al (1977) concluded that changes to operational procedures offer an immediate and inexpensive method to conserve fuel and should be implemented on a priority basis. The operational changes reported in the literature that promote fuel conservation are now discussed.

Aggarwal et al (1979) demonstrated that departure and approach procedures, trajectory optimization, drag reduction by retrimming the aircraft during flight, aircraft and engine maintenance, instrument calibration, reduced engine warm up and taxi time, partial engine taxi, computerized flight planning, and reduced reserve fuel will lead to

fuel conservation. Formation flight is also considered a means for saving fuel. Warner (2002) declared that “It was clear that flying in a lead aircraft’s vortex improved fuel consumption, thus increase range”. Forsyth et al (1973) found that towing aircraft on the ground has a potential to be a feasible way to save fuel. Different approach patterns can also provide fuel savings. Edwards et al (1977) proposed a delayed flap approach to save fuel. Dillingham (2008) mentions that a continuous descent approach, demonstrated in Figure 2-1, also reduces fuel consumption. Another way to save fuel is using air refueling. In his study, Nangia (2006) declared about commercial aircraft that “fuel efficiency peaks at 2,500 – 3,000nm range. Significant fuel savings on long-range journeys could be achieved by replacing the large long-range aircraft with short-range equivalents refueling at intermediate airfields or utilizing air-to-air refueling if air refueling were possible for commercial aircraft”. Visser (2001) also argues that air refueling increases payload and range. Air refueling operations--which are virtually indispensible for military--also bring potential in term of fuel savings. This is investigated more detail in the following sections.

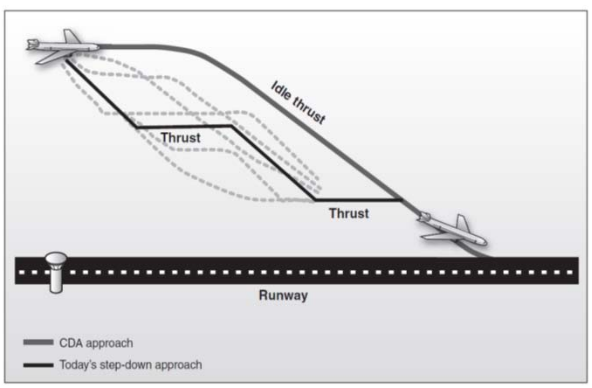

Figure 2-1. Comparison of CDA and Current Step-Down Approach (Dillingham, 2008)

2.1. Air Refueling

Air refueling is the process of transferring fuel from one aircraft (the tanker) to another (the receiver) during flight. Camerer (2001) notes Major General Perry B. Griffith's comment that "No single innovation of recent times has contributed more to air power flexibility than the aerial tanker…" However, air refueling hasn't generally been seen as a way of saving fuel. Camerer (2001) said:

> "Air refueling is a force multiplier that is inherently critical to achieving the rapid global mobility General Robertson described. As a force multiplier, air refueling bridges the gap between the CONUS and the various theaters of operations. This accelerates the deployment cycle and reduces dependency on forward staging bases and host nation support…As a force enhancer, air refueling extends the range, payload and loiter time of combat and combat support forces which allows fighters and bombers to attack strategic and tactical targets, deep in enemy territory, with greater payloads."

That is why during Operations Desert Shield and Desert Storm, approximately 400 tankers offloaded over 1.2 billion pounds of fuel to over 80,000 aircraft while flying over 30,000 sorties and logging over 140,000 hours of flight time (Barnes et al, 2004). "With in-flight refueling, fighter aircraft can fly non-stop from the United States east coast to Saudi Arabia in 15 hours rather than 47 hours required by landing enroute to refuel" (Hostler, 1987). NATO (the North Atlantic Treaty Organization) looks at air refueling as a means of "spatial or temporal extension of other air capabilities like strike, transport" and "This extension is accomplished by providing additional fuel to airborne aircraft. This extension also supports many second order effects like enhancing flexibility, reducing operating locations, and increasing payload capacity" (Future of Air-to Air Refueling in NATO, 2007).

Because a receiver aircraft can be topped up with extra fuel while airborne, air refueling can allow a takeoff with a greater payload of weapons, cargo or personnel. The

maximum take-off weight limit is maintained by carrying less fuel and topping up once airborne. Alternatively, a shorter take-off roll can be achieved because take-off can be at a lighter weight before refueling in flight. In sum, air refueling is a very important operation which has useful features. But can air refueling also conserve fuel?

2.2. Air Refueling and Fuel Conservation

Air refueling is always a significant option for cargo aircraft to accomplish missions beyond their unrefueled range. But refueling is not generally considered if the distance flown is within range, even though air refueling has a potential to save fuel for such missions. There are two ways that air refueling may decrease total fuel consumption for within-range missions. The first way is to decrease gross weight during the takeoff and climb phases, which are the most fuel intensive parts of the flight, by not loading the full fuel needed for the whole flight. The cargo aircraft would be loaded with the same amount of freight as if the mission is planned without air refueling. It is loaded with minimum fuel and reserves which will allow it to take off and go to an air refueling area. There it meets with a tanker aircraft and obtains the fuel needed to fly the remaining mission. This refueling operation will be carried out as soon as the cargo aircraft reaches its cruise altitude. The air refueling is done close to the cargo aircraft’s base. In this approach there is a tradeoff between the fuel savings from “light” aircraft takeoff and climb and the additional fuel used by the tanker aircraft.

The second way is to cut the total required number of cargo aircraft sorties for a given lift task by increasing their payload and using aerial refueling. In this second approach, cargo aircraft are loaded with maximum freight and minimum fuel and reserves to allow them to take off and fly to an air refueling area. There they meet with

tanker aircraft and obtain the necessary fuel to finish the mission. Fewer cargo aircraft sorties may thus be needed to move a given amount of freight. In this scenario, the tradeoff is between the fuel saved by eliminating cargo aircraft sorties versus the additional fuel burned by the tanker aircraft.

The purpose of this research is to investigate the reduced cargo aircraft sorties scenario, which has a greater potential to save fuel than the light takeoff scenario offers. If cargo aircraft sorties can be cut, then the fuel for a whole sortie would be saved instead of saving fuel just during the takeoff and climb portions. In addition, other costs such as aircraft maintenance, crew man-hours for cargo aircraft are avoided and airlift resources are freed for other missions.

Several studies examine air refueling as a means of fuel conservation for both military and commercial aircraft. Nangia (2006) conjectures that significant fuel savings on long range journeys can be achieved by replacing a large long-range aircraft with short-range equivalents that refuel at intermediate airfields or by using air-to-air refueling if air refueling is possible for commercial aircraft. His study is for beyond-unrefueled range distances. Visser (2001) also states that "air refueling increases payload and range. Air refueling operations, which are virtually indispensible for military, also bring potential in terms of fuel savings". His study was based on a very simplified model and assumes a constant fuel burn rate, which is difficult to support for large aircraft. Bennington and Visser (2005) demonstrate the impact of increased payload--at the cost of off-loading fuel at takeoff and acquiring it sometime during flight--on the carrying capability of the aircraft for a given range. They focus on Boeing 747-400, Boeing 777-300 and Airbus A318 aircraft types. However, they also assume a fixed fuel burn rate

during cruise and no cruise fuel usage for the tanker which means that the tanker is located just a climb distance away from the air refueling point. Additionally, their model does not change aircraft routing to minimize total fuel consumption. They assumed that air refueling takes place along the passenger/cargo aircraft route. They concluded that a payload increase can be attained with air refueling. The final relevant study is done by Yamani et al. in 1990. They studied the air refueling location identification problem for a single lifter and tanker, of which the objective is to determine the initial fuel required by each aircraft and the location of the refueling point so as to minimize the total fuel consumed, subject to aircraft range restrictions. They derived the mathematical relationships between fuel consumption, distance traversed, cargo weight and the initial fuel of the aircraft. But their model assumes that everything occurs at altitude. Takeoff, climbing, landing and their costs were ignored. This assumption enables the entire cargo aircraft and tanker flights to represented by the "cruise" phase. Note that their model was built for a single cargo and single tanker aircraft. We relaxed this assumption to include multiple cargo and tanker aircraft. To obtain more realistic results, we also consider start, taxi, APU, takeoff, climb, reserve, alternate, and holding fuels. Another important point is that Yamani et al. assume that aerial refueling takes a negligible amount of time. The region in which fuel transfer takes place is considered to be a point. Conversely, air refueling may take 20-30 minutes and several hundred nautical miles for large cargo aircraft such as the C-5 and C-17, depending on fuel amounts offloaded. This necessitates that air refueling should be considered over a region and not at a point. The final difference is that Yamani et al.'s model does not include freight weight optimization

because it is designed for a single cargo aircraft. We optimize the freight amount loaded on each cargo aircraft.

Because distances traversed by both cargo and tanker aircraft must follow the earth's curvature, they are circular rather than linear. To get more concrete results, all distances are calculated as great circle distances using the haversine formula shown below:

$$\Delta\hat{\sigma} = 2\arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_s\cos\phi_f\sin^2\left(\frac{\Delta\lambda}{2}\right)}\right).$$

(Source for Formula: http://en.wikipedia.org/wiki/Great-circle_distance)

Where,

$\Delta\sigma$: Interior Spherical Angle

$\Delta\Phi$: Latitude1 - Latitude2

Φ_S: Latitude1

Φ_f: Latitude2

$\Delta\lambda$: Longitude1 - Longitude2

This angle multiplied by the radius of the Earth (6371.1 km) yields the great circle distance between two locations.

3. Journal Manuscript

Fuel Savings Opportunities from Air Refueling

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ABSTRACT

Fuel is a critical strategic asset for military aviation operations, yet is increasingly expensive. Air refueling offers both the opportunity to extend aircraft range and the potential to save fuel by enabling a transport aircraft to depart with less fuel in exchange for additional cargo. We evaluate the practicality of air refueling in terms of fuel savings versus distance and cargo quantity, by introducing two non-linear optimization models that examine the tradeoff between departure fuel weight and loaded cargo for given origin, destination, and tanker base positions and freight quantities to be moved. We use two numerical example scenarios to show that substantial fuel savings from air refueling are possible.

Keywords: Nonlinear Programming, Air Refueling, Fuel, Optimization, Energy

3.1. Introduction

Fuel always constrains aircraft operations, not only in terms of range and capacity but also because of its contribution to total operating cost. Gilyard et al (1999) note that airline fuel costs can contribute up to half of the operating expense for larger, long-range transports. The U.S Air Force alone consumed 2.2 billion gallons of aviation fuel in 2007, costing $5.87 billion (Saglam, 2009). Many studies have addressed aircraft fuel consumption in the hope of decreasing operating costs and extending range and capacity.

Pilati (1974) and Hopkins and Wharton (1977) show that changes in operational procedures offer an immediate and inexpensive method to conserve fuel. Our research investigates air refueling as a fuel conservation option. While air refueling is always a significant option for enabling aircraft to reach destinations beyond their unrefueled range, it is seldom used to support aircraft flights within range. However, the takeoff and climb segments of an aircraft's flight are the most fuel-intensive portions of that flight. Hence by exchanging take-off fuel for additional cargo and then later refueling while airborne, it is possible to reduce the total number of cargo aircraft sorties needed to achieve a given air cargo movement requirement. The potential savings are limited by the cargo aircraft's maximum takeoff weight limit and the distance between origin and destination, and the fuel consumed by the tanker aircraft. Our research aims to quantify this savings by extending prior research by Yamani and his colleagues (1990). Our paper proceeds as follows: Section 3.2 provides a review of the literature and discusses Yamani et. al's (1990) model. We introduce our models in Section 3.3 and provide two numerical examples in Section 3.4. We conclude in Section 3.5 with a discussion of model limitations and recommendations for further research.

3.2. Background

The literature includes several studies addressing air refueling as a means of fuel conservation for both military and commercial aircraft. Nangia (2006) examines distances beyond unrefueled range. He notes that for commercial aircraft, "fuel efficiency peaks at 2,500 – 3,000nm range. Significant fuel savings on long-range journeys could be achieved by replacing the large long-range aircraft with short-range

equivalents refueling at intermediate airfields or using air-to-air refueling if air refueling were possible for commercial aircraft". Visser (2001) proposes a simple model and assumes a constant fuel burn rate (which is difficult to support for large aircraft). He found that air refueling increases payload and range, and discusses the potential for air refueling to promote fuel savings. Bennington and Visser (2005) examine the tradeoff of increasing payload at the cost of reducing takeoff fuel and later air-refueling, for cargo aircraft capacity for a given fixed range. In their study, they focus on Boeing 747-400, Boeing 777-300 and Airbus A318 aircraft types. However, they assume a fixed fuel burn rate during cruise and no cruise time for the tanker, implying that the tanker is located just a climb distance away from the air refueling point. Additionally, their model does not adjust cargo or tanker aircraft routing to minimize total fuel consumption. They assumed that the air refueling takes place along the cargo aircraft's route. They conclude that a payload increase can be attained for cargo aircraft with air refueling.

Our research extends the result by Yamani et al. (1990). They studied the air refueling location problem for a single tanker and cargo aircraft, where the objective is to determine the initial fuel required by each aircraft and the refueling point location that minimizes the total fuel consumed, subject to cargo and tanker aircraft range restrictions. They derived mathematical relationships between fuel consumption, distance traversed, cargo weight and initial cargo aircraft fuel. They assume that everything occurs at altitude: takeoff, climbing, and landing fuel and their costs are all ignored. This assumption enables the tanker and receiver flights to be modeled in the "cruise" phase alone. Further, their model was built for a single cargo and single tanker aircraft. We relax these assumptions by including multiple cargo and tanker aircraft, and by

considering start, taxi, auxiliary power, takeoff, climb, reserve, alternate, and holding fuels to achieve more realistic results. A second important point is that Yamani and his colleagues assume that aerial refueling requires a negligible amount of time. They model the fuel transfer region as a single point. However, air refueling may actually take 20-30 minutes and several hundred nautical miles for large cargo aircraft such as the C-5 and C-17, depending on the fuel amount offloaded. This necessitates that air refueling be considered over a region. The final difference is that Yamani et al.'s model doesn't include freight weight optimization because it models only a single cargo aircraft. We determine the required number of sorties for a given transport scenario and optimize the cargo weight loaded for each transport aircraft flight. We conclude this section by reviewing Yamani et al (1990)'s notation and key results as the starting point for our work:

Nomenclature

MPF(GW) : The distance traveled in miles per 1000 pounds of fuel burned when the aircraft gross weight has value GW

GW : Gross weight of aircraft

EW : Empty weight of aircraft

w : Freight load weight of aircraft

g : Fuel amount of aircraft

R(*g*,*w*) : The range of aircraft when its initial fuel is *g* and cargo freight weight is *w*

FC(*g*,*w*,*d*) : The fuel consumed when a cargo aircraft flies a distance *d*, its initial fuel is *g* and its cargo freight weight is *w*.

FR(w,d) : The fuel required by a cargo aircraft to fly a distance d, when freight cargo weight is w;

Cruise fuel consumption is a nonlinear function of airspeed, altitude, and gross weight. Yamani et al develop a linear approximation of this relationship from standard aircraft technical data, where a_0 is an intercept and a_1 is a slope coefficient. The distance travelled in miles per 1,000 pounds of fuel burned by a particular aircraft at its gross weight GW is then:

$$\mathrm{MPF(GW)} = a_0 + a_1.\mathrm{GW}$$

The particular a_0 and a_1 values for the aircraft in our study are shown in Appendix C.

Range Function R(g,w):

$$\mathrm{R}\,(g,w) = [a_0 + a_1(\mathrm{EW} + w + g/2)]g$$

Fuel Consumption Function FC(g,w,d):

$$\mathrm{FC}(g,w,d) = g + \frac{a_0+a_1(\mathrm{EW}+w)}{a_1} - \frac{[\{a_0+a_1(\mathrm{EW}+w+g)\}^2-2a_1 d]^{1/2}}{a_1} \qquad (1)$$

Fuel Requirement Function FR(w,d):

$$\mathrm{FR}(w,d) = g = -\mathrm{EW} - w - \frac{a_0}{a_1} + \frac{[\{a_0+a_1(\mathrm{EW}+w)\}^2+2a_1 d]^{1/2}}{a_1} \qquad (2)$$

3.3. Model Building

Two nonlinear programs are constructed. Model (P1) inputs include the tanker base, cargo aircraft origin, and final destination geographic coordinates, and the total freight weight to be moved. It then computes the optimal geographic location of the rendezvous point at which air refueling begins, initial fuel and freight amount loaded to each cargo aircraft, and the total required tanker and cargo aircraft sorties to minimize

overall fuel consumption. Model (P2) next maximizes the cargo weight of each transport aircraft to move the same total freight from origin to destination without air refueling. We then use the P2 results to determine the total fuel consumption required without air refueling. We finish by comparing the total fuel consumption with and without air refueling. Our fuel consumption and cargo capacity data were obtained from applicable Air Force aircraft technical documentation. Cruise fuel consumption data is provided in Appendix A. Distance traversed and fuel burned during takeoff and climb is given in Appendix B. We followed the same MPF(GW) linear fit process as Yamani et al. (1990) to transform fuel burn data into a form useful for our models (See Appendix C for linear fit results). All distances are calculated as great circle distances by using the haversine formula.

3.3.1. Cargo & Tanker Aircraft Flight Profile

Figure 3-1 shows a basic total flight profile for cargo and tanker aircraft for the air refueling option. First, a transport aircraft takes off from a cargo base α, where we assume all transport aircraft and freight are located. It flies a distance $d_{\alpha\theta}$ to the rendezvous point θ where it meets with a tanker aircraft. The fuel transfer then begins along the destination route, which occurs over a distance d_R . When air refueling is completed, the cargo aircraft continues to its destination Ω and the tanker aircraft returns to the rendezvous point. The tanker flies back and forth on leg d_R to refuel subsequent cargo aircraft until its fuel level drops to a level sufficient to return to the tanker base on leg $\beta\theta$. The amount of fuel that is transferred to each cargo aircraft depends on distances $d_{\beta\theta}$ and $d_{\theta\Omega}$, which in-turn depend on the rendezvous point location.

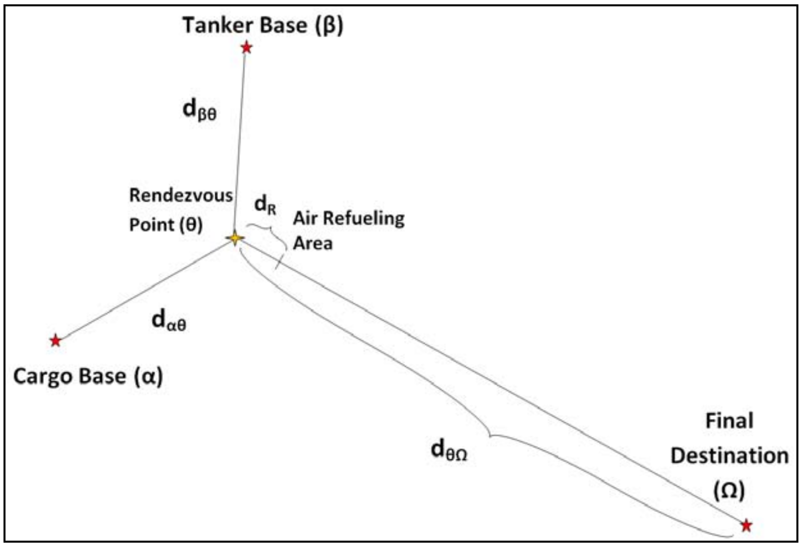


Figure 3-1. Flight Legs

3.3.2. Aircraft Fuel Planning

The following components describe aircraft fuel requirements for a given mission:

- *Start, taxi, auxiliary power unit, takeoff* : This fuel is consumed. The respective amounts are provided in manufacturer flight manual performance data and fuel planning documents as fixed values.
- *Reserve*: 10 percent of flight time fuel (not to exceed one hour of fuel at normal cruise).
- *Alternate*: Fuel from missed approach at the destination to a point above an alternate airport if the destination airport is closed because of weather or an accident.
- *Holding*: Fuel for possible waiting in the air because of traffic congestion at the alternate location.

Note that reserve, alternate and holding fuel are for long delays or visibility issues in poor weather conditions. In this study, no such conditions are assumed, so reserve, alternate and holding fuel is carried but not used.

- *Climb*: the fuel consumed during climb to cruise altitude. We assume both cargo and tanker aircraft cruise at the same altitude.
- *Cruise*: Fuel consumed after an aircraft attains its cruise altitude. Since aircraft weight changes over time, the cruise fuel burn rate also changes. We use equations 1 and 2 to calculate cruise fuel.

We combine *descent*, *approach* and *landing* fuel with cruise fuel to mitigate model complexity. Since actual descent, approach and landing fuel usage does not exceed (and is typically less than) cruise fuel consumption, our model yields conservative results.

3.3.3. Assumptions and Notation

Assumptions

- Each cargo aircraft is loaded with identical freight weight and initial fuel.
- Air refueling begins at the same rendezvous point for each aircraft.
- Air refueling is performed at cruise speed and cruise altitude
- There are no cargo load balance or size restrictions.
- Aircraft scheduling is perfect. No aircraft are late to a refueling event.
- The earth is a perfect sphere and aircraft follow great circle routes.

➢ Winds at altitude are negligible. Temperature and other weather considerations represent standard conditions as noted in associated technical orders or performance documents.

➢ Both cargo and tanker aircraft cruise at 31,000 feet. The a_0 and a_1 constants are derived for this altitude. (See Appendix A, B, and C)

➢ During air refueling, the tanker and cargo aircraft fuel burn rates are equal to their respective cruise fuel burn rates and do not change due to transferred fuel weight or deployed tanker boom drag.

➢ If a tanker aircraft's remaining offloadable fuel is less than the cargo aircraft's need, then the tanker offloads all its offloadable fuel. Another tanker immediately gets in position and offloads the remaining required fuel. The time required for formation changes is negligible.

➢ Cargo aircraft carry no cargo while returning from destination to origin. Thus, the fuel consumed during return is considered in the model as waste when calculating the total fuel savings.

Notation

$\boldsymbol{\Phi}$	Refueling point latitude (decision variable)
$\boldsymbol{\lambda}$	Refueling point longitude (decision variable)
$\boldsymbol{g}$	Initial cargo aircraft fuel load (decision variable, lbs)
$\boldsymbol{w}$	Freight weight loaded on each cargo aircraft (decision variable, lbs)
$\boldsymbol{w_{Last}}$	Freight weight loaded to last cargo aircraft in problem P2
$\mathbf{N^C}$	Number of cargo aircraft needed to move total freight (decision variable)
$\mathbf{N^T}$	Number of tanker aircraft needed to refuel N^C (decision variable)
$\mathbf{EW^C}$	Cargo aircraft empty weight
$\mathbf{EW^T}$	Tanker aircraft empty weight
$\mathbf{MTOW^C}$	Cargo aircraft maximum takeoff weight

$\mathbf{MTOW^T}$	Tanker aircraft maximum takeoff weight
$\mathbf{R^C}$	Cargo aircraft reserve + alternate + holding fuel
$\mathbf{R^T}$	Tanker aircraft reserve + alternate + holding fuel
$\mathbf{S^C}$	Cargo aircraft start + taxi + takeoff fuel
$\mathbf{S^T}$	Tanker aircraft start + taxi + takeoff fuel
$\mathbf{C^C}$	Cargo aircraft climb fuel
$\mathbf{C^T}$	Tanker aircraft climb fuel
$\mathbf{K^C}$	Cargo aircraft total fuel capacity
$\mathbf{K^T}$	Tanker aircraft total fuel capacity
$\mathbf{F^T}$	Maximum fuel amount that can be loaded to a tanker aircraft on the ground
$\mathbf{V^T}$	Approximate fuel burn rate of tanker aircraft (lbs/hr)
h	Tanker aircraft boom fuel transfer rate (lbs/hr)
TW	Total freight weight
$\mathbf{FC^C[(\mathit{g}),(\mathit{w}),(\mathit{d})]}$	Fuel consumed when a cargo aircraft flies a distance d, its initial fuel is g and its cargo freight weight is w; using equation 1
$\mathbf{FR^C[(\mathit{w}),(\mathit{d})]}$	Fuel required by a cargo aircraft to fly a distance d, when freight cargo weight is w; using equation 2
$\mathbf{FC^T[(\mathit{g}),(\mathit{w}),(\mathit{d})]}$	Fuel consumed by a tanker aircraft to fly a distance d, when its initial fuel is g and its cargo freight weight is w; using equation 1
$\mathbf{FR^T[(\mathit{w}),(\mathit{d})]}$	Fuel required by a tanker aircraft to fly a distance d, when freight cargo weight is w; using equation 2
$\mathbf{FC^C_{\alpha\theta}}$	Fuel consumption of cargo aircraft on leg $d_{\alpha\theta}$
$\mathbf{FC^C_{\theta\Omega}}$	Fuel consumption of cargo aircraft on leg $d_{\theta\Omega}$
$\mathbf{FC^C_{\Omega\alpha}}$	Fuel consumption of cargo aircraft on leg $d_{\Omega\alpha}$
$\mathbf{FC^T_{\beta\theta}}$	Fuel consumption of tanker aircraft on leg $d_{\beta\theta}$ to go to rendezvous point
$\mathbf{FC^T_R}$	Fuel consumption of tanker aircraft during air refueling
$\mathbf{FC^T_{\theta\beta}}$	Fuel consumption of tanker aircraft on leg d_3 to turn back to its base
Y1	Total Fuel consumption from problem P1
Y2	Total Fuel consumption from problem P2

$\boldsymbol{\alpha}$	Cargo base location
$\boldsymbol{\beta}$	Tanker base location
$\boldsymbol{\theta}$	Rendezvous point location
$\boldsymbol{\Omega}$	Final destination location
$\boldsymbol{d_{\alpha\theta}}$	Great circle distance between α and θ
$\boldsymbol{d_{\theta\Omega}}$	Great circle distance between θ and Ω
$\boldsymbol{d_{\beta\theta}}$	Great circle distance between β and θ
$\boldsymbol{d_R}$	Great circle distance traversed during air refueling
$\boldsymbol{d_{\Omega\alpha}}$	Great circle distance between Ω *and* α
$\boldsymbol{d_{TC}^{C}}$	Distance traversed during takeoff and climb by cargo aircraft
$\boldsymbol{d_{TC}^{T}}$	Distance traversed during takeoff and climb by tanker aircraft
$\boldsymbol{g_{off}}$	Amount of fuel offloaded to each cargo aircraft from tanker aircraft
Q	Number of cargo aircraft that can be refueled by one tanker aircraft

3.3.4. Problem Formulation

Cargo Aircraft Fuel:

The fuel needed by each cargo aircraft for the air refueling option is comprised of three components:

The fuel needed for distance $d_{\alpha\theta}$ is based on equation 1 plus two additional fuel terms:

$$\mathrm{FC}_{\alpha\theta}^{\mathrm{C}} = \mathrm{S}^{\mathrm{C}} + \mathrm{C}^{\mathrm{C}} + \mathrm{FC}^{\mathrm{C}}[(g - \mathrm{S}^{\mathrm{C}} - \mathrm{C}^{\mathrm{C}}), (w), (d_{\alpha\theta} - d_{TC}^{C})];$$

Fuel offloaded in the air to each cargo aircraft combines equations 1 and 2 plus a reserve fuel term:

$$g_{off} = \mathrm{FR}^{\mathrm{C}}[(\mathrm{w} + \mathrm{R}^{\mathrm{C}}), (d_{\theta\Omega})] - g + \mathrm{FC}_{\alpha\theta}^{\mathrm{C}} + \mathrm{R}^{\mathrm{C}};$$

Fuel consumption for distance $d_{\theta\Omega}$ augments equation 2 to obtain:

$$\mathrm{FC}_{\theta\Omega}^{\mathrm{C}} = g - \mathrm{FC}_{\alpha\theta}^{\mathrm{C}} - \mathrm{R}^{\mathrm{C}} + g_{off} = \mathrm{FR}^{\mathrm{C}}[(w + \mathrm{R}^{\mathrm{C}}), (d_{\theta\Omega})]$$

Note that $w = w + \mathrm{R}^{\mathrm{C}}$, because R^{C} represents fuel that is carried but not used.

Fuel consumption on leg $\Omega\alpha$ includes fuel for all flight portions noted in Section 3.3.2:

$$\mathrm{FC}^{\mathrm{C}}_{\Omega\alpha} = \mathrm{S}^{\mathrm{C}} + \mathrm{C}^{\mathrm{C}} + \mathrm{FR}^{\mathrm{C}}[(\mathrm{R}^{\mathrm{C}}), (d_{\Omega\alpha} - d^{C}_{TC})]$$

Tanker Aircraft Fuel:

Tanker aircraft are assumed to takeoff fully loaded with fuel to be able to refuel the greatest possible number of cargo aircraft. We comment that K^{T} may or may not be equal to F^{T} depending upon $\mathrm{MTOW}^{\mathrm{T}}$ and EW^{T}. Note that if $\mathrm{K}^{\mathrm{T}} + \mathrm{EW}^{\mathrm{T}} \leq \mathrm{MTOW}^{\mathrm{T}}$, then $\mathrm{F}^{\mathrm{T}} = \mathrm{K}^{\mathrm{T}}$; otherwise, $\mathrm{F}^{\mathrm{T}} = \mathrm{MTOW}^{\mathrm{T}} - \mathrm{EW}^{\mathrm{T}}$. There are 3 components to total tanker aircraft fuel consumption. The first component addresses the fuel used for distance $d_{\beta\theta}$ to reach the rendezvous point:

$$\mathrm{FC}^{\mathrm{T}}_{\beta\theta} = \mathrm{S}^{\mathrm{T}} + \mathrm{C}^{\mathrm{T}} + \mathrm{FC}^{\mathrm{T}}[(\mathrm{F}^{\mathrm{T}} - \mathrm{S}^{\mathrm{T}} - \mathrm{C}^{\mathrm{T}}), 0, \left(d_{\beta\theta} - d^{T}_{TC}\right)]$$

The second component examines fuel consumption during air refueling. This amount depends on the number of cargo aircraft refueled by one tanker aircraft and the quantity of offloaded fuel. If the boom transfer rate is h (lbs/hr.), it takes $\frac{2.g_{off}}{h}$ hours to refuel each aircraft (note that the multiplier 2 emerges because the tanker flies a distance $2d_R$ for each refueling event). Then, the total fuel consumption during air refueling becomes:

$$\mathrm{FC}^{\mathrm{T}}_{\mathrm{R}} = \mathrm{Q}.\frac{2\, g_{off}}{h}\, .\mathrm{V}^{\mathrm{T}}$$

The third component—the tanker fuel consumed while returning to its base across distance $d_{\beta\theta}$, is now addressed. The tanker will offload all its transferrable fuel and it does not itself carry cargo. Note that R^{T} must be included on-board, and hence $w = \mathrm{R}^{\mathrm{T}}$ to obtain:

$$\mathrm{FC}^{\mathrm{T}}_{\theta\beta} = \mathrm{FR}^{\mathrm{T}}[(\mathrm{R}^{\mathrm{T}}), (d_{\beta\theta})]$$

We can next derive Q, the number of cargo aircraft that can be refueled by one tanker.

$$Q = \frac{F^T - R^T - FC^T_{\beta\theta} - FC^T_{\theta\beta} - \frac{2Q.\,g_{off}.\,V^T}{h}}{g_{off}}$$

Simplifying, we obtain

$$Q = \frac{h.(F^T - R^T - FC^T_{\beta\theta} - FC^T_{\theta\beta})}{g_{off}.(h + 2V^T)}.$$

We now can define problem P1, which minimizes the total fuel consumption for both cargo aircraft and tankers for the air refueling option, as:

P1: *Minimize* $Y1 = N^C.\left[FC^C_{\alpha\theta} + FC^C_{\theta\Omega} + FC^C_{\Omega\alpha}\right] + N^T.\left[FC^T_{\beta\theta} + FC^T_{R} + FC^T_{\theta\beta}\right]$

Subject to

$$w.N^C \geq TW \quad \text{(a)}$$

$$\frac{N^C}{Q} - N^T \leq 0 \quad \text{(b)}$$

$$EW^C + w + g \leq MTOW^C \quad \text{(c)}$$

$$g \leq K^C \quad \text{(d)}$$

$$FC^C_{\theta\Omega} + R^C \leq K^C \quad \text{(e)}$$

$$w \leq \text{Cargo aircraft cargo capacity} \quad \text{(f)}$$

$$EW^C + w + FC^C_{\theta\Omega} + R^C \leq \text{Max Inflight operation weight} \quad \text{(g)}$$

$$d_{\beta\theta} - d^T_{TC} \geq 0 \quad \text{(h)}$$

$$d_{\alpha\theta} - d^C_{TC} \geq 0 \quad \text{(i)}$$

$$g \geq FC^C_{\alpha\theta} \quad \text{(j)}$$

$$FC^C_{\Omega\alpha} + R^C \leq K^C \quad \text{(k)}$$

$$-90 \leq \Phi \leq 90, \quad \text{(l)}$$

$$-180 \leq \lambda \leq 180 \qquad \text{(m)}$$

$$g, w, N^C, N^T \geq 0 \qquad \text{(n)}$$

$$N^C, N^T \quad \text{integer} \qquad \text{(o)}$$

Constraint (a) requires that all freight be moved, while (b) forces the tanker aircraft to perform the air refueling. Constraint (c) prevents a loaded cargo aircraft from exceeding its maximum takeoff weight. Constraints (d) and (e) preclude the respective initial on-ground and post air-refueling fuel capacities from exceeding the cargo aircraft's storage limits. Constraint (f) prevents a cargo aircraft from being overloaded, while (g) assures that the cargo aircraft gross weight just after air refueling doesn't exceed the aircraft's total allowable weight in the air. When calculating $d_{\alpha\theta}$ and $d_{\beta\theta}$, we exclude the distance traversed during takeoff and climb to have the correct distance to use in the fuel consumption function for cruise. Constraints (h) and (i) prevent negative distance values so that the fuel consumption functions are correct for cruise. These two constraints together force the rendezvous point to be optimized at least d_{TC} miles away from the tanker and cargo bases. Constraint (j) requires the cargo aircraft to obtain enough initial fuel to reach the rendezvous point. Constraint (k) assures that the total fuel on board while the cargo aircraft is flying back empty is less than its maximum fuel capacity. Constraints (l) and (m) provide latitudes and longitude boundaries. Constraints (n) and (o) enforce non-negativity and integrality conditions on the respective variables.

A solution to problem P1 provides rendezvous point coordinates, cargo and fuel amounts for each cargo aircraft, total required cargo and tanker aircraft sorties to move the total freight and total fuel consumption. Problem P2 is then solved. It maximizes the cargo weight of each cargo aircraft to move the same amount of total freight from origin

to destination as in problem P1, but without air refueling. The problem P2 formulation is shown below:

P2: *Maximize w*

Subject to

$$\mathrm{S^C + C^C + FR^C}[(w + \mathrm{R^C}), (d_{\Omega\alpha} - d^C_{TC})] + \mathrm{R^C + EW^C} + w \leq \mathrm{MTOW^C} \quad \text{(p)}$$

$$\mathrm{S^C + C^C + FR^C}[(w + \mathrm{R^C}), (d_{\Omega\alpha} - d^C_{TC})] + \mathrm{R^C} \leq \mathrm{K^C} \quad \text{(q)}$$

$$w \leq \text{Cargo Capacity} \quad \text{(r)}$$

Constraint (p) limits the maximum takeoff weight, (q) limits available fuel capacity, while (r) limits overall cargo capacity per cargo aircraft. Note that the only decision variable in problem P2 is *w*. Given the maximized cargo weight, Equation 3 calculates the total fuel consumption. Its development proceeds as follows: first, the integer number of cargo aircraft sorties needed to move the total freight requirement without air refueling is computed as:

$$\lceil \mathrm{N^C} \rceil = \frac{TW}{w}$$

Based on *w* and the total freight amount, the last transport aircraft's cargo weight (w_{Last}) may be less than the other aircraft loads. Hence, the last aircraft's cargo weight is:

$$w_{Last} = \mathrm{TW} - [(\mathrm{N^C} - 1). w]$$

Therefore, the total fuel used by all transport aircraft sorties is:

$$\mathrm{Y2} = \mathrm{S^C + C^C + FR^C}[(w_{Last} + \mathrm{R^C}), (d_{\Omega\alpha} - d^C_{TC})] + \quad (3)$$
$$\left[(\mathrm{N^C} - 1). (\mathrm{S^C + C^C + FR^C}[(w + \mathrm{R^C}), (d_{\Omega\alpha} - d^C_{TC)}])\right] + \left[\mathrm{N^C}. \mathrm{FC}^{\mathrm{C}}_{\Omega\alpha}\right]$$

Consequently, if Y1 – Y2 ≤ 0, then the air refueling option is practical. Otherwise, it is impractical.

3.4. Validation

The U. S. Air Force Air Mobility Command (AMC) uses Advanced Computer Flight Plan (ACFP) software for actual fuel requirement planning for the aircraft considered in this study. To validate our model, two example scenarios involving a single cargo and tanker aircraft were delivered to AMC to conduct actual mission fuel planning for both the “air refueling” and “without air refueling” options. The first scenario focuses on a C-5 / KC-10 pair and the second is for a C-17 / KC-135 pair. For both scenarios, the respective origin / destination and tanker bases are McChord Air Force Base / Eldorado International Airport in Bogota, Colombia and Travis Air Force Base. Our algorithms predetermined the rendezvous point at (32º 56' 26'' N and 104º 25' 35'' W), and then the ACFP software solved the fuel planning problem for this rendezvous point. Required ramp fuel is the initial fuel load for aircraft on the ground. For the tanker aircraft, required ramp fuel includes start, taxi, takeoff and climb fuel, reserve alternate and holding fuel, offloaded fuel to one cargo aircraft, and cruise fuel. Additionally, the cruise fuel consumed during air refueling is considered as the fuel amount consumed during refueling one cargo aircraft.

The results are shown in Table 3-1 and Table 3-2. Our model’s results for every fuel computation are within 7% of the respective ACFP output.

Table 3-1. Comparison of the Results of ACFP and Our Model for C-5 and KC-10 Aircraft

	Study	ACFP	% Difference
Required Ramp Fuel of Cargo Aircraft for "Without Air Refueling Option" to go from Origin to Destination (lbs)	256,811	259,014	-0.85
Required Ramp Fuel of Cargo Aircraft for "Without Air Refueling Option" to Turn back from Destination to Origin (Carrying no Cargo) (lbs)	226,017	231,095	-2.20
Max Cargo Weight without Air Refueling (lbs)	132,189	131,375	0.62
Required Ramp Fuel of Tanker Aircraft for Air Refueling Option (to Refuel 1 Cargo Aircraft) (lbs)	288,183	280,000	2.92

Table 3-2. Comparison of the Results of ACFP and Our Model for C-17 and KC-135 Aircraft

	Study	ACFP	% Difference
Required Ramp Fuel of Cargo Aircraft for "Without Air Refueling Option" to go from Origin to Destination(lbs)	198,904	201,400	-1.24
Required Ramp Fuel of Cargo Aircraft for "Without Air Refueling Option" to Turn back from Destination to Origin (Carrying no Cargo) (lbs)	173,856	171,862	1.16
Max Cargo Weight without Air Refueling (lbs)	103,596	98,011	5.70
Required Ramp Fuel of Tanker Aircraft for Air Refueling Option (to Refuel 1 Cargo Aircraft) (lbs)	138,654	130,000	6.66

3.5. Numerical Examples

We illustrate our models with two scenarios involving two different cargo aircraft and two different tanker aircraft types, and different origin, destination and tanker base locations. Scenarios were run for various total cargo quantities in addition to various tanker base locations and tanker-cargo aircraft pairs to capture the relationship between total fuel savings with air refueling, distance, aircraft type and total cargo amount. The first scenario is a mid-range origin-destination distance which is representative for United States east coast-west coast deployments. The second scenario is a longer distance scenario which is representative for continental United States - Europe deployments.

We used Excel Solver® for all optimization computations. Since our model is nonlinear, the solutions that the solver finds which satisfies all optimality conditions and constraints is only guaranteed to be locally optimal. Hence, potential savings may be even greater than the values we report.

Scenario 1

This is a mid-range distance scenario. The distance between origin and destination is 2,151 nautical miles. The total freight to be moved is 5,000,000 lbs. Appendices A-C

contain aircraft performance data, while Appendix D includes additional Scenario 1 inputs. Table 3-3 depicts the Scenario 1 outputs. (See Appendix D for optimum rendezvous coordinates). For this scenario, air refueling saves fuel for the C-5 / KC-10, C-5 / KC-135 and C-17 / KC-135 aircraft pairs. The C-5 / KC-135 pair yields the highest savings of 754,038 pounds of fuel. Note that air refueling is not practical for the C-17 / KC-10 option.

Table 3-3. Scenario-1 Outputs

	C-5 / KC-10		**C-5 / KC-135**	
	Air Refueling Option	**No Air Refueling Option**	**Air Refueling Option**	**No Air Refueling Option**
Cargo Aircraft Sorties Needed	19	25	19	25
Tanker Aircraft Sorties Needed	7	0	10	0
Each Cargo Aircraft's Cargo Load (lbs)	263,158	202,336	263,158	202,336
Each Cargo Aircraft's Initial Fuel Load (lbs)	114,773	186,664	125,166	186,664
Total Fuel Consumption (lbs)	5,347,144	5,977,497	5,223,460	5,977,497
Conclusion	AIR REFUELING OPTION IS PRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	630,354		754,038	
Total Lifter Sorties Saved	6		6	
Additional Tanker Sorties Needed	7		10	
	C-17 / KC-10		**C-17 / KC-135**	
	Air Refueling Option	**No Air Refueling Option**	**Air Refueling Option**	**No Air Refueling Option**
Cargo Aircraft Sorties Needed	30	32	30	32
Tanker Aircraft Sorties Needed	6	0	6	0
Each Cargo Aircraft's Cargo Load (lbs)	166,667	156,757	166,667	156,757
Each Cargo Aircraft's Initial Fuel Load (lbs)	102,668	145,743	120,114	145,743
Total Fuel Consumption (lbs)	6,349,734	6,170,817	6,124,170	6,170,817
Conclusion	AIR REFUELING OPTION IS IMPRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	-178,916		46,648	
Total Lifter Sorties Saved			2	
Additional Tanker Sorties Needed	6		6	

Figure 3-2 shows the flight routes and the approximate rendezvous point. Figure 3-3 plots the total fuel savings from air refueling versus total cargo moved this scenario. For C-5 aircraft a positive correlation is observed between the total cargo moved and fuel savings from air refueling. As more total freight is moved, more fuel is saved with air refueling. For the C-17-KC-10 pair, air refueling is impractical for almost all cargo amounts. For the C-17 KC-135 pair, fuel savings with air refueling is generally just above the zero level. One of the important reasons why air refueling can save fuel is that it reduces needed cargo aircraft sorties, so that all fuel consumed--not only from origin to destination but also for the empty return trip--is avoided.

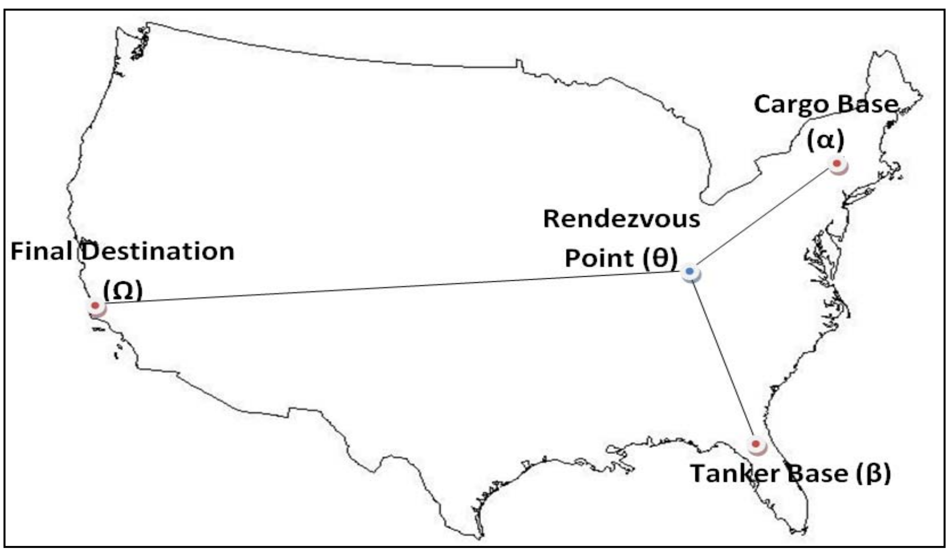


Figure 3-2. Routes and Rendezvous Point on Map for Scenario 1

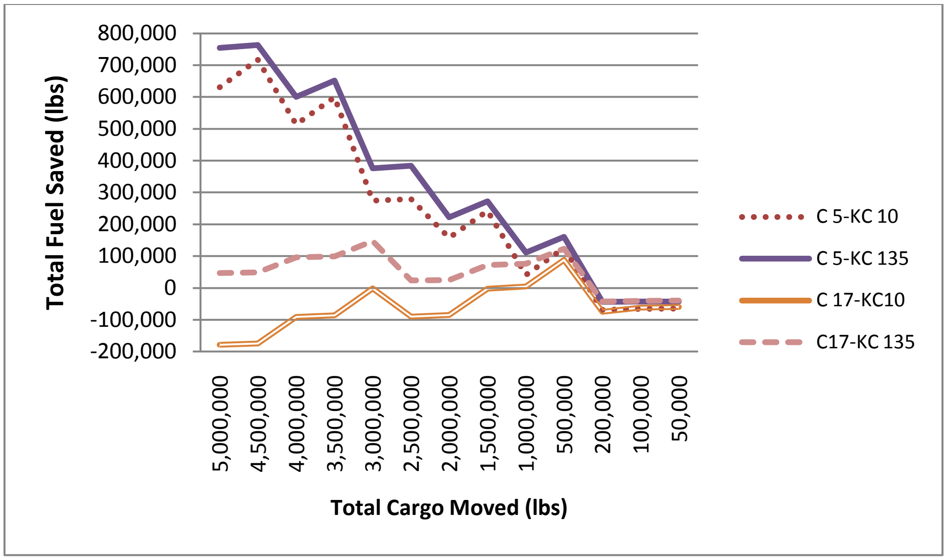


Figure 3-3. Total Fuel Savings with Air Refueling vs. Total Cargo Moved For Scenario 1

Note that as the total required cargo decreases, air refueling becomes impractical for all aircraft pairs in this scenario. For the C-5 / KC-135 and C-5 / KC-10 pairs, this cargo breakeven point is 202,000 lbs. If the total cargo requirement is less than 202,000 lbs, then air refueling costs more in terms of fuel consumption than the option with no air refueling. The breakeven point is 480,000 lbs for the C-17 / KC-135 pair.

The distance between the tanker base and the rendezvous point also affects the fuel savings from air refueling. For this scenario the distance is approximately 410 nautical miles. If a tanker base closer to the rendezvous point is used, then the total fuel savings will increase because the tanker aircraft fuel consumption will decrease. For example, if Scott AFB is used as the tanker base for the same scenario, then the fuel savings from air refueling increases substantially for the 5,000,000 lbs of cargo since the distance between the tanker base and rendezvous point drops to approximately 190 NM (see Table 3-4).

Table 3-4. Fuel Savings from Air Refueling for Scott AFB as Tanker Base

	Fuel Savings From Air Refueling(lbs)
C-5-KC-10	1,051,523
C-5-KC-135	1,072,111
C-17-KC-10	133,359
C-17-KC-135	231,444

Table 3-5 shows the proportion of fuel savings contributed by reducing the number of sorties of empty cargo aircraft returning from the destination to the base of origin. These flights –termed *inactive leg* sorties by AMC—account for a significant proportion of the overall fuel savings—efficient scheduling could mitigate the savings effect by using these flights for other cargo. However, we note that these return trips are not the only source of savings. The C-5 / KC-10 and C-5 / KC-135 pairs both show that air refueling can save overall fuel, even if we account for the inactive leg trips.

Table 3-5. Proportion of Savings from Inactive Leg Sorties in Total Fuel Savings

Tanker Base	C-5 / KC-10	C-5 / KC-135	C-17 / KC-10	C-17 / KC-135
Florida	100%	85%	-	100%
Scott AFB	61%	60%	100%	100%

We next examine the possible dollar savings, using the year 2010 AMC-published charter rates and aircraft speeds given in appendix B. The savings from air refueling for scenario 1 with 2 different tanker base locations are shown in Table 3-6 and 3-7:

Table 3-6. Cost Savings from Air Refueling for Scenario 1 (Tanker Base: Florida)

		C-5 / KC-10	C-5 / KC-135	C-17 / KC-10	C-17 / KC-135
"Air Refueling" Option	**Cost of All Cargo Aircraft**	$ 5,368,103	$5,347,349	$ 4,099,028	$4,083,453
	Cost of All Tanker Aircraft	$ 407,608	$ 495,384	$ 364,927	$ 317,484
	Total Cost	$ 5,775,711	$5,842,734	$ 4,463,955	$ 4,400,937
"No Air Refueling" Option	**Total Cost**	$ 6,996,533	$6,996,533	$ 4,349,051	$4,349,051
Cost Savings from Air Refueling		$1,220,822	$1,153,799	$ -114,904	$ -51,886

Table 3-7. Cost Savings from Air Refueling for Scenario 1 (Tanker Base: Scott AFB)

		C-5 / KC-10	C-5 / KC-135	C-17 / KC-10	C-17 / KC-135
"Air Refueling" Option	Cost of All Cargo Aircraft	$ 5,321,534	$ 5,327,653	$ 4,080,446	$ 4,083,314
	Cost of All Tanker Aircraft	$ 142,112	$ 153,790	$ 170,535	$ 102,527
	Total Cost	$ 5,463,647	$ 5,481,443	$ 4,250,981	$ 4,185,840
"No Air Refueling" Option	Total Cost	$ 6,996,533	$ 6,996,533	$ 4,349,051	$ 4,349,051
Cost Savings from Air Refueling		$1,532,886	$ 1,515,090	$ 98,070	$ 163,211

Note that the C-5 / KC-10 pair yields the highest cost savings from air refueling, at over $1.5 million. Using tanker base locations closer to the air refueling point would increase the cost savings. C-5 pairs result in savings for all tanker basing options.

Scenario 2

Scenario 2 is a longer-range scenario which is representative of continental United States - Europe deployments. McGuire Air Force Base was selected as both the cargo and tanker base. Ramstein Air Base in Germany is the destination. The distance between origin and destination is 3,338 NM and total freight is 5,000,000 lbs (See Appendix D for other inputs). The Scenario 2 results are shown in Table 3-8.

Table 3-8. Scenario 2 Outputs

	C-5 / KC-10		C-5 / KC-135	
	Air Refueling Option	No Air Refueling Option	Air Refueling Option	No Air Refueling Option
Cargo Aircraft Sorties Needed	20	36	20	36
Tanker Aircraft Sorties Needed	13	0	21	0
Each Cargo Aircraft's Cargo Load (lbs)	250,000	142,719	250,000	142,719
Each Cargo Aircraft's Initial Fuel Load (lbs)	136,236	246,281	136,108	246,281
Total Fuel Consumption (lbs)	8,891,996	12,705,906	8,740,337	12,705,906
Conclusion	AIR REFUELING OPTION IS PRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	3,813,909		3,965,569	
Total Lifter Sorties Saved	16		16	
Additional Tanker Sorties Needed	13		21	

	C-17 / KC-10		C-17 / KC-135	
	Air Refueling Option	**No Air Refueling Option**	**Air Refueling Option**	**No Air Refueling Option**
Cargo Aircraft Sorties Needed	30	45	30	45
Tanker Aircraft Sorties Needed	11	0	18	0
Each Cargo Aircraft's Cargo Load (lbs)	166,667	111,174	166,667	111,174
Each Cargo Aircraft's Initial Fuel Load (lbs)	133,827	191,326	131,783	191,326
Total Fuel Consumption (lbs)	10,072,126	12,595,830	9,927,165	12,595,830
Conclusion	AIR REFUELING OPTION IS PRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	2,523,704		2,668,666	
Total Lifter Sorties Saved	15		15	
Additional Tanker Sorties Needed	11		18	

For this scenario, air refueling provides fuel savings for all cargo-tanker aircraft pairs. The highest savings is with the C-5 / KC-135 pair, at over 3.8 million lbs. Appendix D shows the optimum rendezvous point coordinates.

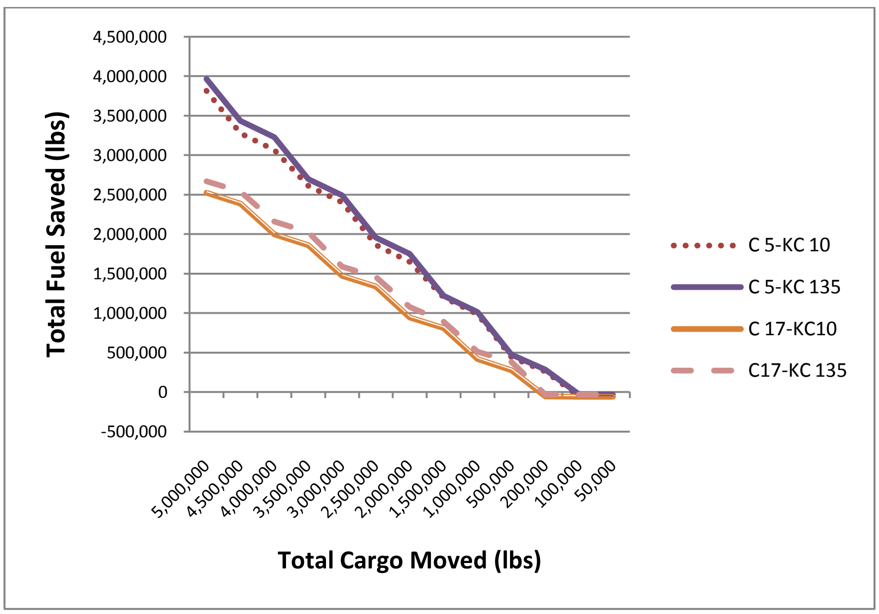


Figure 3-4. Total Fuel Savings with Air Refueling vs. Total Cargo Moved For Scenario 2

Figure 3-4 shows total fuel savings with air refueling plotted against total cargo moved. The positive correlation between total cargo amount and fuel savings from air refueling is clear. In this scenario, C-5 aircraft yield more fuel savings than C-17 aircraft.

Furthermore, all aircraft pairs yield greater savings from air refueling than observed in Scenario 1, since the distance between the origin and the destination is greater in Scenario 2. The breakeven point for all cargo-tanker aircraft pairs is around 200,000 lbs of cargo which means that if the total cargo amount is less than 200,000 lbs then air refueling becomes impractical for saving fuel.

Table 3-9 shows the proportion of savings contributed by inactive leg sorties. Again the C-5 / tanker pairs show that significant savings are possible, even after accounting for the inactive legs.

Table 3-9. Proportion of Savings from Inactive Leg Sorties in Total Fuel Savings

C-5/KC-10	C-5/KC-135	C-17/KC-10	C-17/KC-135
68%	65%	100%	100%

The dollar cost savings based on AMC charter hourly rates for scenario 2 are shown in Table 3-10. The C-5 / KC-10 pair saves over $6 million by air refueling. This is the highest observed result of the cargo / tanker aircraft pairs. All aircraft pairs indicate that dollar savings are possible.

Table 3-10. Cost Savings from Air Refueling for Scenario 2

		C-5 / KC-10	C-5 / KC-135	C-17 / KC-10	C-17 / KC-135
"Air Refueling" Option	Cost of All Cargo Aircraft	$8,684,139	$8,684,139	$6,326,096	$6,326,096
	Cost of All Tanker Aircraft	$ 936,831	$1,234,588	$1,004,877	$1,361,289
	Total Cost	$9,620,971	$9,918,728	$7,330,973	$7,687,384
"No Air Refueling" Option	Total Cost	$15,632,030	$15,632,030	$9,489,144	$9,489,144
Cost Savings from Air Refueling		$6,011,059	$ 5,713,302	$2,158,171	$1,801,759

3.6. Conclusion and Discussion

Our research substantially improves upon the existing model proposed by Yamani et al. for estimating the fuel savings opportunities from air refueling. We were able to extend their result to both capture more realistic fuel usage and consider multiple cargo and tanker aircraft. We also optimize the freight weight allocated to each cargo aircraft. Our method and results—validated by comparison to operational flight fuel estimation software output—show that substantial fuel savings are possible from air refueling, by quantifying the tradeoff between initial fuel and loaded cargo weight. For U.S. Air Force applications, the C-5 / KC-135 pair yields the highest air refueling-based fuel savings in both of the scenarios we studied. However, the C-5 / KC-10 pair yields the highest dollar cost savings. The fuel and cost savings achievable from air refueling grows when:

- the tanker base is moved closer to the air refueling point,
- the amount of cargo to be moved increases,
- the distance between origin and destination increases.

A breakeven point exists for the total amount of cargo to be moved, which is around 100,000 to 400,000 lb for our aircraft and scenarios examined. If the total cargo lift requirement is less than this point air refueling becomes impractical.

Because additional flight costs are associated with using tanker aircraft, the unit cost of fuel offloaded in the air is greater than the unit cost of fuel delivered on the ground. When we ignore these other cost components associated with a given sortie and assume that fuel is the only cost, then a fuel cost ratio can be computed. When this ratio exceeds the breakeven points shown in Table 3-11 for our given scenarios, then the air refueling option costs more than the "no air refueling option," even though it saves fuel.

Table 3-11. Breakeven Fuel Cost Ratios

	Breakeven Fuel Cost Ratio			
	C-5 / KC-10	C-5 / KC-135	C-17 / KC-10	C-17 / KC-135
Scenario 1 (Tanker Base Florida)	1.397	1.549	-	1.058
Scenario 1 (Tanker Base Scott AFB)	1.797	1.734	1.084	1.238
Scenario 2	2.395	2.449	2.223	2.259

We acknowledge that mission planning and associated fuel calculations may vary in real life. For example, our model's computations assumed that the cruise and air refueling altitude is 31,000 feet for all aircraft. In real life, optimum cruise altitudes may be different which changes the fuel calculations.

Secondly, this study doesn't cover the factors that can hinder or prevent the execution of air refueling such as aircrew or aircraft unavailability, tanker and/or cargo aircraft failure during air refueling, bad weather conditions at rendezvous point, etc.

A final limitation of the model concerns tanker aircraft fuel consumption. Tanker aircraft fuel usage is calculated based on its ability to refuel an integer number of cargo aircraft. If the number of cargo aircraft refuelable by one tanker is not integer-valued, then the model can't precisely capture the tanker aircraft fuel consumption during air refueling. However, our interviews with a KC-10 pilot and the model's agreement with ACFP software indicate that our model provides a reasonable approximation to actual usage.

4. Illustrative Example: Brigade Concept Team Deployment

Chapter 3 presents two broad overview scenarios as numerical examples. This chapter provides additional real-life examples by assessing possible fuel savings for the air refueling option used in an Army brigade combat team deployment. Mahan et al (2004) note:

> "In October 1999, the Army's Chief of Staff issued a vision statement to transform the service, including the goal of deploying a combat force anywhere in the world within 96 hours after liftoff. The Army defined this combat force as a "middle-weight" brigade combat team—a force between the weight of an existing light and heavy brigade. The Army's vision for this interim brigade combat team (IBCT) has significant implications for USTRANSCOM and the Defense Transportation System. Their target is to have the entire IBCT deploy within 96 hours of first aircraft wheels-up and begin operations immediately after arriving at the aerial port of debarkation."

Mahan et al (2004) conducted a United States Transportation Command transportability analysis of the Army's vision for a prototype Stryker brigade termed the Interim Brigade Combat Team (IBCT). They examined the force closure of an IBCT from seven home-station locations (referred to as origins) to eight worldwide destinations. Each destination represented a potential geographic region of future conflict (see Figure 4-1). They assume that the move requirement includes about 1,500 wheeled vehicles, almost 3,900 soldiers, and three days of supplies, for a total of 14,660 short tons of materiel--equal to 29,320,000 lbs. In our study, C-5 and C-17 cargo aircraft are the focus along with KC-10 and KC-135 tankers. Since the Eielson-Sri Lanka, Elmendorf-Sri Lanka, McChord-Angola and Wheeleer Sack-Congo origin-destination pairs are out of the unrefueled range of C-5 and C-17 aircraft, these pairs are not included. The practicality of employing air refueling is evaluated for the remaining origin-destination pairs in terms of fuel conservation. The main airports in the capital cities of the

destination countries shown in Figure 4-1 are selected as destination points. Several possible tanker base locations are evaluated. We assumed that sufficient KC-10 or KC-135 aircraft are located at the tanker base locations before the deployment begins.

	IBCT Destinations							
	South America		Central Asia	Sub-Saharan Africa			South Pacific	Europe
IBCT Origin	Colombia	Venezuela	Sri Lanka	Angola	Democratic Republic of Congo	Sierra Leone	Papua New Guinea	Balkans
McChord AFB (Fort Lewis)	X			X				X
Alexandria IAP (Fort Polk)		X						
Wheeler-Sack AAF (Fort Drum)					X	X		
Hickam AFB (Schofield Barracks)							X	
Eielson AFB (Fort Wainwright)			X					
Elmendorf AFB (Fort Richardson)			X					
Ramstein AB (Coleman Barracks)					X			

Figure 4-1 Origin-Destination Pairs for Potential Future Conflict Areas

4.1. Scenarios

Scenario 1 (McChord AFB-Colombia Pair)

For this scenario, the McChord Air Force Base – Colombia Bogota El Dorado International Airport origin-destination pair is evaluated along with 6 different tanker base locations. The distance between origin and destination is 3,558 NM. Travis AFB in California, McDill AFB in Florida, Alexandria International Airport in Louisiana, Altus AFB in Oklahoma, Salt Lake International Airport in Utah, and Sky Harbor International Airport in Arizona are the tanker base locations. We found that air refueling is practical for all aircraft pairs and tanker base locations for this scenario. Furthermore, the Altus AFB and C-5 / KC-135 pair yields the highest fuel savings from air refueling, at over 34,134,000 lbs. The results for this scenario are shown in Table 4-1. Travis AFB saves

the least fuel for all aircraft pairs. (See Appendix E for the results of all tanker locations and aircraft pairs.)

Table 4-1. Highest Fuel Saver Option Outputs for Scenario-1 (C-5 / KC-135 and Altus AFB)

Rendezvous Point Coordinates			
Degrees	Minutes	Seconds	Hemisphere
34	4	5	N
101	41	51	W
		Air Refueling Option	No Air Refueling Option
Cargo Aircraft Sorties Needed		116	222
Tanker Aircraft Sorties Needed		107	0
Each Cargo Aircraft's Cargo Load (lbs)		252,759	132,203
Each Cargo Aircraft's Initial Fuel Load (lbs)		136,241	256,797
Total Fuel Consumption (lbs)		49,069,139	83,203,179
Conclusion		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)		34,134,040	
Total Lifter Sorties Saved		106	
Additional Tanker Sorties Needed		107	

Figure 4.2 shows the results for the routes and rendezvous point, using Travis AFB as the tanker base location.

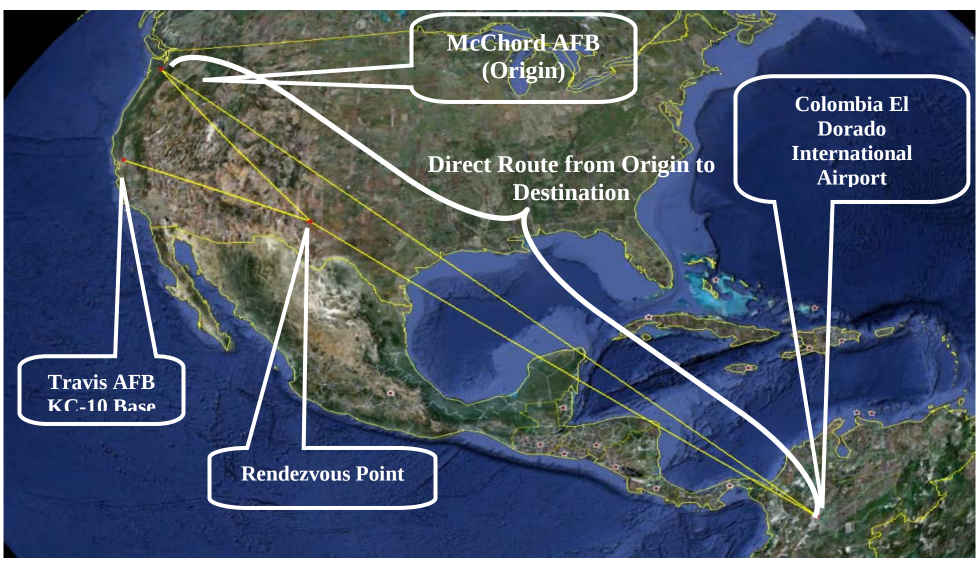


Figure 4-2. Routes and Rendezvous Point on Map for Scenario 1

Scenario 2 (Alexandria IAP-Venezuela Pair)

For this scenario, the Fort Polk (Alexandrian international Airport)-Venezuela Simon Bolivar International Airport origin-destination pair is evaluated along with five different tanker base locations. The distance between origin and destination is 1,904 NM. Travis AFB in California, Alexandria IAP in Louisiana, Key Field ANGB in Mississippi, Birmingham IAP in Alabama, and McDill AFB in Florida are considered as tanker base locations. We found that air refueling is impractical for all C-17 options, but is practical for most C-5 options. Additionally, Travis AFB is the least preferable tanker base for air refueling operations for all aircraft pairs. McDill AFB and the C-5 / KC-135 pair yields the highest fuel savings from air refueling, at about 4,321,000 lbs. This result is shown in Table 4-2 (See Appendix E for the results of all tanker locations and aircraft pairs.)

Table 4-2. Highest Fuel Saver Option Outputs for Scenario-2 (C-5 / KC-135 and McDill AFB)

Rendezvous Point Coordinates			
Degrees	**Minutes**	**Seconds**	**Hemisphere**
25	**47**	**59**	**N**
82	**49**	**18**	**W**
		Air Refueling Option	**No Air Refueling Option**
Cargo Aircraft Sorties Needed		109	137
Tanker Aircraft Sorties Needed		41	0
Each Cargo Aircraft's Cargo Load (lbs)		268,991	215,415
Each Cargo Aircraft's Initial Fuel Load (lbs)		119,794	173,585
Total Fuel Consumption (lbs)		25,170,857	29,491,851
Conclusion		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)		4,320,993	
Total Lifter Sorties Saved		28	
Additional Tanker Sorties Needed		41	

Scenario 3 (Wheeler Sack AAF-Sierra Leone Pair)

For this scenario, the Fort Drum (Wheeler Sack)-Sierra Leone Lungi International Airport origin-destination pair is evaluated along with five different tanker base locations. The distance between origin and destination is 3,866 NM. McGuire AFB, Semour Johnson AFB, McDill AFB, Roosevelt Roads in Puerto Rico and Lajes Field in Portugal are the candidate tanker base locations. Air refueling is practical for all aircraft and city pairs. Lajes Field and the C-5 / KC-135 pair yields the highest fuel savings from air refueling, which is 40,884,435 lbs. The results are shown in Table 4-3. (See Appendix E for the results of all tanker locations and aircraft pairs.)

Table 4-3. Highest Fuel Saver Option Outputs for Scenario-3 (C-5 / KC-135 and Lajes Field)

Rendezvous Point Coordinates			
Degrees	Minutes	Seconds	Hemisphere
38	37	54	N
42	38	27	W
		Air Refueling Option	No Air Refueling Option
Cargo Aircraft Sorties Needed		124	250
Tanker Aircraft Sorties Needed		135	0
Each Cargo Aircraft's Cargo Load (lbs)		236,452	117,647
Each Cargo Aircraft's Initial Fuel Load (lbs)		152,548	271,353
Total Fuel Consumption (lbs)		60,202,865	101,087,300
Conclusion		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)		40,884,435	
Total Lifter Sorties Saved		126	
Additional Tanker Sorties Needed		135	

In Figure 4-3, routes and approximate rendezvous points for Lajes Field and Roosevelt Roads can be seen on the map.

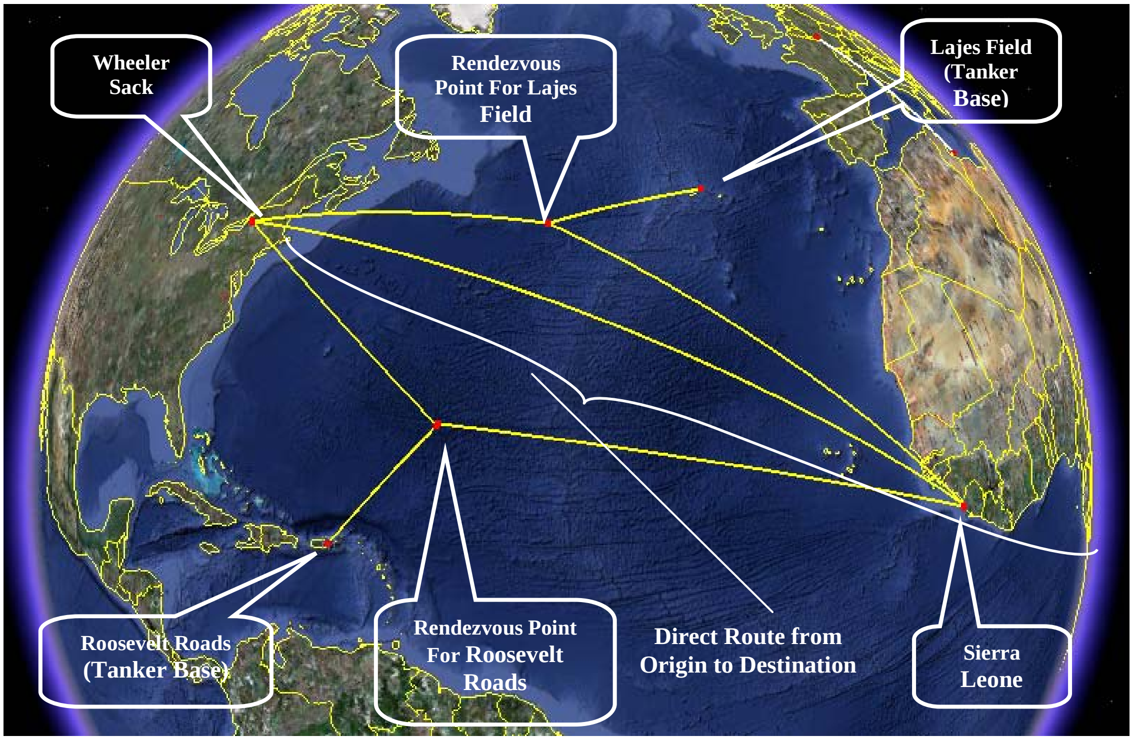


Figure 4-3. Routes and Approximate Rendezvous Points for Scenario 3

Scenario 4 (Ramstein AB-Democratic Republic of Congo Pair)

For this scenario, the Ramstein Air Base in Germany and Democratic Republic of Congo origin-destination pair is evaluated along with three different tanker base locations. The distance between the origin and destination is 3,257 NM. Ramstein Air Base in Germany, Aviano Air Base in Italy and Carthage IAP in Tunisia are the tanker base locations. Air refueling is practical for all aircraft and city pairs. Carthage IAP and the C-5 / KC-135 pair yields the highest fuel savings from air refueling, which is over 24,747,300 lbs. Results are shown in Table 4-4. (See Appendix E for the results of all tanker locations and aircraft pairs.)

Table 4-4. Highest Fuel Saver Option Outputs for Scenario-4 (C-5 / KC-135 and Carthage IAP)

Rendezvous Point Coordinates			
Degrees	**Minutes**	**Seconds**	**Hemisphere**
32	**42**	**32**	**N**
10	**54**	**13**	**E**

	Air Refueling Option	No Air Refueling Option
Cargo Aircraft Sorties Needed	112	200
Tanker Aircraft Sorties Needed	101	0
Each Cargo Aircraft's Cargo Load (lbs)	261,786	146,614
Each Cargo Aircraft's Initial Fuel Load (lbs)	127,205	242,386
Total Fuel Consumption (lbs)	44,462,105	69,209,400
Conclusion	AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	24,747,295	
Total Lifter Sorties Saved	88	
Additional Tanker Sorties Needed	101	

Scenario 5 (Hickam AFB-Papua New Guinea Pair)

For this scenario, the Hickam Air Force Base-Papua New Guinea Jacksons International Airport origin-destination pair is evaluated along with three different tanker base locations. The distance between origin and destination is 3,724 NM. Hickam Air Force Base in Hawaii, Anderson Air Base in Guam and Kadena Air Base in Japan are the tanker base locations. Air refueling is practical for all aircraft and city pairs. Hickam AFB and the C-5 / KC-135 pair yields the highest fuel savings from air refueling, which is 34,716,214 lbs. Results are shown in Table 4-5. (See Appendix E for the results of all tanker locations and aircraft pairs.)

Figure 4-4 depicts routes and approximate rendezvous points for Hickam AFB, Anderson AB and Kadena AB.

Table 4-5. Highest Fuel Saver Option Outputs for Scenario-5 (C-5 / KC-135 and Hickam AFB)

Rendezvous Point Coordinates			
Degrees	**Minutes**	**Seconds**	**Hemisphere**
12	**10**	**46**	**N**
176	**40**	**3**	**W**

	Air Refueling Option	No Air Refueling Option
Cargo Aircraft Sorties Needed	119	236
Tanker Aircraft Sorties Needed	155	0
Each Cargo Aircraft's Cargo Load (lbs)	246,387	124,323
Each Cargo Aircraft's Initial Fuel Load (lbs)	142,396	264,677
Total Fuel Consumption (lbs)	60,504,328	92,220,543
Conclusion	AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	31,716,214	
Total Lifter Sorties Saved	117	
Additional Tanker Sorties Needed	155	

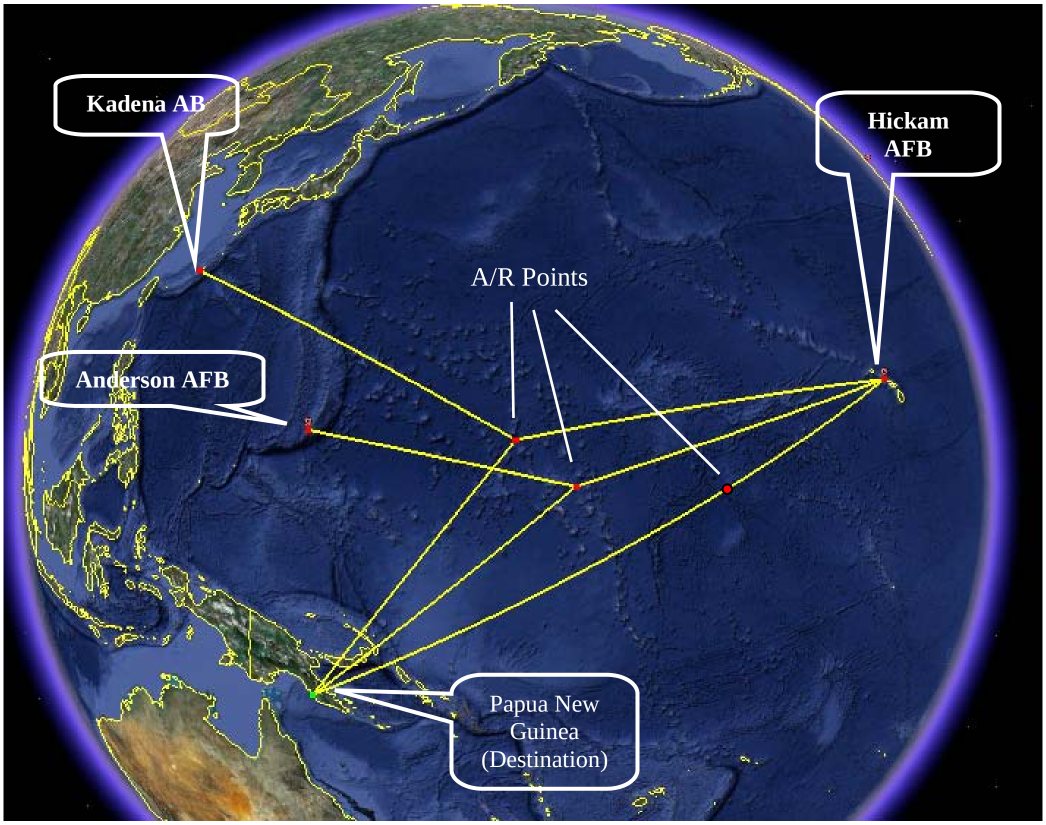


Figure 4-4. Routes and Approximate Rendezvous Points for Scenario 5

4.2. Limitations

The purpose of this study is to show potential fuel savings achievable via air refueling, which is not generally considered a way of saving fuel. Mission planning/fuel calculations may vary in real life because of the assumptions used in this study. For example, one of the model assumptions is that the cruise and refueling altitude is 31,000 feet for all aircraft. But in real life, the optimum cruise altitudes may be different based on aircraft capabilities and weather, which could change fuel calculations.

Another important limitation is associated with the risk of air refueling. This study doesn't cover the factors that can prevent air refueling execution such as tanker and/or cargo aircraft failure during air refueling, bad weather conditions at rendezvous point, etc. In a scenario in which tanker aircraft have to abort during air refueling, both tanker aircraft and cargo aircraft will have to land at the closest base which would increase total fuel consumption.

The final model limitation concerns tanker aircraft fuel consumption. Fuel consumption of the tanker aircraft on its route is calculated using an integer number of cargo aircraft. However, if the number of cargo aircraft that can be refueled by one tanker is not an integer number, e.g., if one tanker can refuel only 2.25 cargo receivers, then the model can't capture the precise tanker aircraft fuel consumption during air refueling. To better understand this limitation, first we need to understand the logic of a detailed tanker aircraft mission profile (see Figure 4-5). Tanker fuel consumption is comprised of three components: first, the tanker takes off from β and flies to θ. This is the fuel consumption to reach the rendezvous point. Recall that our model assumes air refueling begins at this point for each of the cargo aircraft, which means that the tanker begins air refueling at

this point and flies a distance d_R for the first cargo aircraft. It finishes the refueling job at point B. Then it flies back to θ to meet another cargo aircraft. The second cargo aircraft refueling process is the same. But since the tanker can only refuel 2.25 aircraft, it can only offload 25% of the third cargo aircraft's need. It offloads this amount which ends at point A. In real life, it should fly directly from this point to its base. But the model assumes it returns to θ and then proceeds to β which actually yields a conservative fuel consumption result. Meanwhile, the next tanker should come directly to point A and offload the remaining 75% of the fuel requirement of the third cargo aircraft. Since the geometry is calculated for integer numbers of cargo aircraft for a single tanker, the model assumes the second tanker comes from β to θ, and then to point A. The fuel consumed by the second tanker to go from θ to A is not captured by the model. However, since this distance is a fraction of d_R, and d_R itself is not a long distance (maximum of 150 NM in any scenario), this limitation does not affect the general model validity. Furthermore, interviews with a KC-10 pilot and the model's agreement with ACFP results validates the approximate fuel consumption calculated for tanker aircraft.

4.3. Further Studies

There are risks associated with air refueling. Aircraft reliability should be taken into consideration in deciding whether to use air refueling as a means of fuel conservation. So, a more comprehensive model that also includes the probability of air refueling mission aborts due to aircraft failure or weather is recommended as a future research area. Furthermore, flight mission planning is a very complex issue and has more components than the ones covered in this study. As more complex and comprehensive models are built more precise results can be obtained in terms of fuel consumed and

saved. Another potential future research area for fuel savings is the implication of air refueling for civilian aircraft. Since this study doesn't cover scheduling, extending this study in terms of scheduling and ground support is warranted.

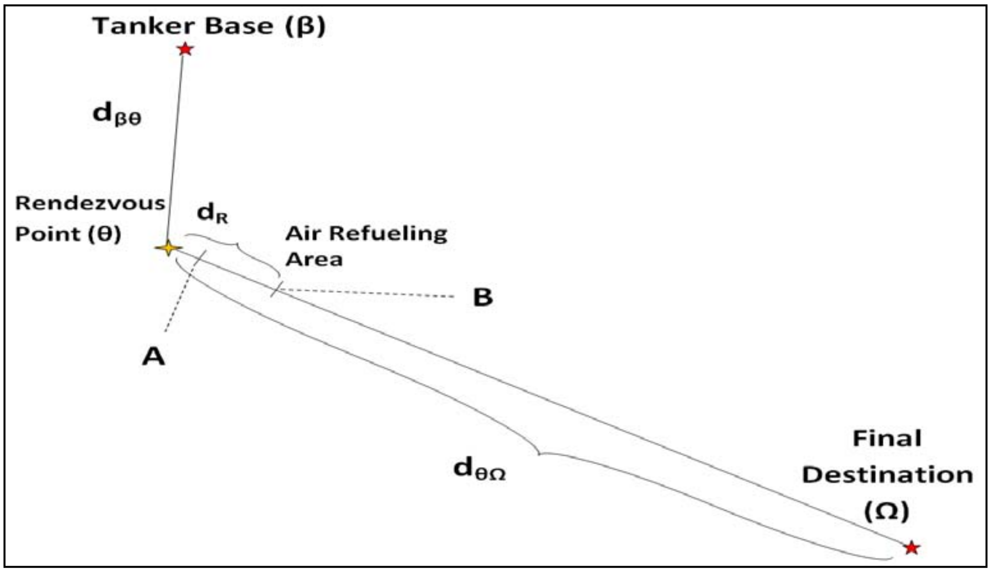


Figure 4-5 Air Refueling Route

Appendix A: Cruise Fuel Information (31,000 feet)

C-17		KC-10		KC-135	
NM Per 1000 Pounds of fuel (Y)	**Gross Weight (X) (1000 lbs)**	**NM Per 1000 Pounds of fuel (Y)**	**Gross Weight (X) (1000 lbs)**	**NM Per 1000 Pounds of fuel (Y)**	**Gross Weight (X) (1000 lbs)**
35.1	280	38.1	240	65.2	120
34	300	36.5	260	63	130
32.8	320	35	280	61.2	140
31.6	340	33.5	300	59.3	150
30.4	360	32.1	320	57.5	160
29.3	380	30.8	340	55.8	170
28.3	400	29.7	360	54.1	180
27.3	420	28.7	380	52.6	190
26.4	440	27.6	400	51.2	200
25.5	460	26.6	420	49.6	210
24.7	480	25.6	440	48.3	220
23.9	500	24.7	460	46.8	230
23.1	520	23.9	480	45.5	240
22.1	540	23	500	44.3	250
21.3	560	22.1	520	43.1	260
20.4	580	21	540	41.8	270
		20	560	40.6	280
		19.1	580	39.4	290
				38.3	300
				37.2	310
				36	320
				34.9	330

(Derived from Flight Manual Performance Data Books (TO-1-1s) Specific Range 31,000 Feet Chart 99% Max Range Line) (Toydas, 2010).

This table shows the relationship of the distance travelled in miles per 1,000 pounds of fuel burned versus the Gross Weight of the aircraft.

Appendix B: Aircraft Facts Summary Table

	C-5	C-17	KC-10	KC-135
a0*	36.2829	48.05426	49.74066	80.206437
a1*	-0.027	-0.0484	-0.0538	-0.1412
Distance to Climb (31,000 feet) (NM)	300***	315	190	125
Empty Weight (lbs)	380,000	282,500	241	119,230
Max Takeoff Weight (lbs)	769,000	585,000	590,000	322,500
Max Inflight Weight (lbs)	840,000	585,000	N/A	N/A
Total Fuel Capacity (K) (lbs)	347,000	241,357	356,000	212,000
Max. Fuel on the Ground (F) (lbs)	347,000	241,357	349,000	203,270
Cargo Capacity (lbs)	270,000	170,900	N/A	N/A
Reserve Fuel (lbs)**	17,390	13,851	6,232	3,714
Alternate Fuel (lbs)**	14,197	7,715	14,820	6,944
Holding Fuel (lbs)**	22,399	17,335	18,918	8,137
Start Taxi Takeoff Fuel (lbs)	3,000	4,500	4,000	2,500
Climb Fuel (31,000 feet) (lbs)	25,000***	22,500	16,000	7,500
Approximate Fuel Burn Rate (lbs/hr)	23,450	21,440	17,755	10,921
Boom Fuel Transfer Rate (lbs/hr)	N/A	N/A	480,000	360,000
Flying Hour Rate ($)******	26,988	12,317	14,261	11,020
Air Speed (mph)******	415	390	425	385

This data is compiled from table in Appendix A, operations procedures volume-3 documents of each aircraft, AFPAM 10-1403 Air Mobility Planning Factors and Fact Sheets of each aircraft published at U.S Air Force official web page (www.af.mil).
*See Appendix C for regression plots and regression summary. For C-5, see Yamani et al (1990).

** Reserve and Alternate fuel amounts are gathered from actual Advanced Computer Flight Plan Software for the scenario mentioned in the validation section. Additionally, the same amount of reserve, alternate and holding fuel is assumed to be used for all scenarios.
***Since no data is available in C-5 Fuel Planning Pamphlet, these data are derived by approximating C-17 data.
**** FY10 DoD Charter Hourly Rates and Minimum Activity Rates for Aircraft on TWCF Missions and Airspeeds (Source: Air Mobility Command)

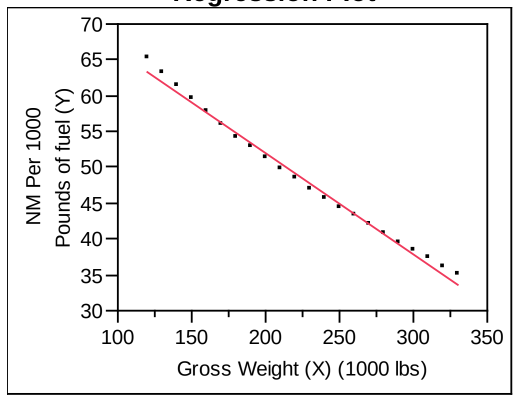
Appendix C: Linear Fit Results for Fuel Consumption vs. Gross Weight

KC-135

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.995841896
R Square	0.991701083
Adjusted R Square	0.991286137
Standard Error	0.85935612
Observations	22

Regression Plot



KC-10

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.995242255
R Square	0.990507146
Adjusted R Square	0.989913843
Standard Error	0.580074192
Observations	18

Regression Plot

C-17

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.997261714
R Square	0.994530926
Adjusted R Square	0.994140277
Standard Error	0.35340778
Observations	16

Regression Plot

Appendix D: Numerical Example Inputs and Optimum Rendezvous Points

Scenario-1 Inputs

Cargo Base Coordinates	42º 05' 56"	N	74º 31' 07"	W
Tanker Base Coordinates	28º 51' 06"	N	81º 23' 57"	W
Destination Coordinates	34º 47' 12"	N	119º 52' 31"	W
Total Freight	5,000,000	lbs		

Scenario-2 Inputs

Cargo Base Coordinates	40º 01' 17"	N	73º 35' 26"	W	**McGuire AFB**
Tanker Base Coordinates	40º 01' 17"	N	73º 35' 26"	W	**McGuire AFB**
Destination Coordinates	49º 26' 10"	N	07º 35' 04"	E	**Ramstein AB, Germany**
Total Freight	5,000,000	lbs			

Scenario-1 Optimum Rendezvous Point Coordinates

	C-5-KC-10		**C-5-KC-135**		**C-17-KC-10**		**C-17-KC-135**	
Rendezvous Point	38º 44' 27"	N	39º 23' 56"	N	39º 35' 52"	N	40º 38' 08"	N
	87º 29' 52"	W	88º 15' 16"	W	87º 17' 58"	W	88º 05' 45"	W

Scenario-2 Optimum Rendezvous Point Coordinates

	C-5-KC-10		**C-5-KC-135**		**C-17-KC-10**		**C-17-KC-135**	
Rendezvous Point	48º 06' 16"	N	48º 06' 16"	N	50º 11' 37"	N	50º 11' 37"	N
	56º 16' 42"	W	56º 16' 42"	W	49º 07' 25"	W	49º 07' 25"	W

Appendix E: Chapter 4 Scenario Results for Different Tanker Bases

Scenario 1

Origin		McChord AFB			47º 07' 25" N	122º 28' 35" W	
Destination		El Dorado International Airport, Bogota, Colombia			04º 42' 37" N	74º 10' 08" W	
		Tanker Base					
		Travis AFB, CA	McDill AFB, FL	Alexandria IAP, LA	Altus AFB, OK	Salt Lake IAP, UT	Sky Harbor IAP, AZ
C-5 - KC-10	Rendezvous Point	33 1 59 N 104 28 32 W	33 16 55 N 94 30 8 W	33 26 33 N 97 11 22 W	37 36 45 N 97 55 0 W	34 25 48 N 103 2 16 W	32 8 48 N 105 16 44 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	116	124	121	116	116	116
	Tanker Sorties Needed	84	69	62	67	79	71
	Each Cargo Aricraft Cargo Load (lbs)	252,784	236,452	242,314	252,759	252,845	252,802
	Each Cargo Aricraft Initial Fuel Load (lbs)	135,555	152,548	146,686	136,241	134,183	134,539
	Total Fuel Savings With Air Refueling (lbs)	27,829,770	28,343,559	32,036,208	33,204,066	29,533,358	32,038,290
	Cargo Sorties Saved with Air Refueling	106	98	101	106	106	106
	Additional Tanker Sorties with Air Refueling	84	69	62	67	79	71
C-5 - KC-135	Rendezvous Point	33 9 46 N 104 21 48 W	33 32 24 N 95 9 32 W	34 34 56 N 98 56 35 W	34 4 5 N 101 41 51 W	34 30 8 N 103 0 5 W	32 11 54 N 105 15 7 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	116	123	118	116	116	116
	Tanker Sorties Needed	137	115	110	107	127	116
	Each Cargo Aricraft Cargo Load (lbs)	252,759	238,374	248,475	252,759	252,759	252,759
	Each Carco Aricraft Initial Fuel Load (lbs)	133,674	150,626	140,525	136,241	135,769	135,012
	Total Fuel Savings With Air Refueling (lbs)	28,769,658	29,007,262	32,441,539	34,134,040	30,368,649	32,482,745
	Cargo Sorties Saved with Air Refueling	106	99	104	106	106	106
	Additional Tanker Sorties with Air Refueling	137	115	110	107	127	116

Origin		McChord AFB			47º 07' 25" N	122º 28' 35" W	
Destination		El Dorado International Airport, Bogota, Colombia			04º 42' 37" N	74º 10' 08" W	
		Tanker Base					
		Travis AFB, CA	McDill AFB, FL	Alexandria IAP, LA	Altus AFB, OK	Salt Lake IAP, UT	Sky Harbour IAP, AZ
C-17 - KC-10	Rendezvous Point	29 34 18 N	30 7 24 N	30 30 14 N	31 42 50 N	30 36 3 N	29 9 35 N
		98 56 56 W	89 58 16 W	89 33 33 W	96 26 16 W	97 49 50 W	99 21 58 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	172	172	172	172	172	172
	Tanker Sorties Needed	76	56	52	54	71	63
	Each Cargo Aricraft Cargo Load (lbs)	170,465	170,465	170,465	170,523	170,465	170,465
	Each Carco Aricraft Initial Fuel Load (lbs)	131,774	132,035	132,035	130,290	131,187	130,590
	Total Fuel Savings With Air Refueling (lbs)	21,557,649	27,870,933	28,970,451	28,613,623	23,203,682	25,778,622
	Cargo Sorties Saved with Air Refueling	113	113	113	113	113	113
	Additional Tanker Sorties with Air Refueling	76	56	52	54	71	63
C-17 - KC-135	Rendezvous Point	29 41 30 N	29 58 2 N	29 2 18 N	31 42 58 N	30 38 51 N	29 18 6 N
		98 49 28 W	90 8 33 W	92 31 34 W	96 28 34 W	97 46 36 W	99 13 27 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	172	172	172	172	172	172
	Tanker Sorties Needed	121	91	85	88	113	101
	Each Cargo Aricraft Cargo Load (lbs)	170,465	170,465	170,465	170,465	170,465	170,465
	Each Cargo Aricraft Initial Fuel Load (lbs)	131,569	132,035	130,011	131,495	131,760	131,865
	Total Fuel Savings With Air Refueling (lbs)	22,790,364	28,273,676	29,689,708	28,881,827	24,231,062	26,423,456
	Cargo Sorties Saved with Air Refueling	113	113	113	113	113	113
	Additional Tanker Sorties with Air Refueling	121	91	85	88	113	101

Scenario 2

Origin		Alexandria IAP			31º 02' 22" N	93º 11' 21" W
Destination		Simon Bolivar IAP, Venezuela			10º 36' 14" N	67º 00' 43" W
		Tanker Base				
		Travis AFB, CA	**Alexandria IAP, LA**	**Key Field, MS**	**Birmingham IAP, AL**	**McDill AFB, FL**
C-5 - KC-10	**Rendezvous Point**	27 41 55 N	27 49 58 N	28 38 48 N	28 54 53 N	24 42 37 N
		88 11 1 W	88 3 58 W	87 29 13 W	87 20 23 W	82 12 11 W
	Air Refueling Practicality	IMPRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	122	109	109	109	109
	Tanker Sorties Needed	25	27	27	27	25
	Each Cargo Aricraft Cargo Load (lbs)	240,328	268,991	268,991	268,991	268,991
	Each Cargo Aricraft Initial Fuel Load (lbs)	147,995	119,767	118,252	119,524	119,620
	Total Fuel Savings With Air Refueling	-1,394,113	3,532,560	3,697,660	3,558,985	4,166,588
	Cargo Sorties Saved with Air Refueling	-	28	28	28	28
	Additional Tanker Sorties with Air Refueling	25	27	27	27	25
C-5 - KC-135	**Rendezvous Point**	27 45 30 N	27 49 58 N	28 32 37 N	28 47 43 N	25 47 59 N
		88 7 49 W	88 3 58 W	87 32 56 W	87 24 11 W	82 49 18 W
	Air Refueling Practicality	IMPRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	126	109	109	109	109
	Tanker Sorties Needed	27	45	44	45	41
	Each Cargo Aricraft Cargo Load (lbs)	232,698	268,991	268,991	268,991	268,991
	Each Cargo Aricraft Initial Fuel Load (lbs)	156,226	118,998	119,116	118,840	119,794
	Total Fuel Savings With Air Refueling	-438,425	3,670,944	3,842,251	3,688,187	4,320,993
	Cargo Sorties Saved with Air Refueling	-	28	28	28	28
	Additional Tanker Sorties with Air Refueling	27	45	44	45	41

Origin		Alexandria IAP			31º 02' 22" N	93º 11' 21" W
Destination		Simon Bolivar IAP, Venezuela			10º 36' 14" N	67º 00' 43" W
		Tanker Base				
		Travis AFB, CA	**Alexandria IAP, LA**	**Key Field, MS**	**Birmingham IAP, AL**	**McDill AFB, FL**
C-17 - KC-10	**Rendezvous Point**	27 30 14 N 88 2 12 W	27 41 55 N 87 51 54 W	28 39 10 N 87 11 58 W	29 1 11 N 87 0 41 W	24 42 2 N 82 22 39 W
	Air Refueling Practicality	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL
	Cargo Sorties Needed	172	172	172	172	172
	Tanker Sorties Needed	35	35	35	35	35
	Each Cargo Aricraft Cargo Load (lbs)	170,465	170,465	170,465	170,465	170,465
	Each Cargo Aricraft	107,163	84,945	83,598	84,530	81,511
	Total Fuel Savings With Air Refueling (lbs)	-5,211,071	-1,389,486	-1,157,960	-1,318,164	-681,154
	Cargo Sorties Saved with Air Refueling	-	-	-	-	-
	Additional Tanker Sorties with Air Refueling	35	35	35	35	35
C-17 - KC-135	**Rendezvous Point**	27 35 59 N 87 56 56 W	27 41 53 N 87 51 51 W	28 11 45 N 87 28 56 W	28 21 28 N 87 22 30 W	25 50 41 N 83 4 55 W
	Air Refueling Practicality	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL	IMPRACTICAL
	Cargo Sorties Needed	172	172	172	172	172
	Tanker Sorties Needed	35	35	35	35	35
	Each Cargo Aricraft Cargo Load (lbs)	170,465	170,465	170,465	170,465	170,465
	Each Cargo Aricraft Initial Fuel Load (lbs)	117,366	105,098	104,461	105,038	102,569
	Total Fuel Savings With Air Refueling (lbs)	-2,597,065	-486,958	-377,489	-476,645	-52,019
	Cargo Sorties Saved with Air Refueling	-	-	-	-	-
	Additional Tanker Sorties with Air Refueling	35	35	35	35	35

Scenario 3

Origin	Wheeler Sack AAF	44º 02' 44"	N	75º 43' 32"	W
Destination	Sierra Leone Lungi Intl. Airport	08º 37' 16"	N	13º 12' 39"	W

		Tanker Base				
		McGuire AFB	Semour Johnson AFB	McDill AFB	Roosevelt Roads	Lajes Field
C-5 - KC-10	Rendezvous Point	35 32 6 N 52 38 22 W	34 11 52 N 54 57 16 W	31 40 46 N 56 52 38 W	26 26 22 N 55 23 3 W	38 42 41 N 41 47 58 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	124	126	127	122	125
	Tanker Sorties Needed	94	98	108	92	81
	Each Cargo Aricraft Cargo Load (lbs)	236,452	232,698	230,866	240,328	234,560
	Each Cargo Aricraft Initial Fuel Load (lbs)	151,526	154,830	157,861	148,672	154,440
	Total Fuel Savings With Air Refueling	36,745,478	34,523,837	30,760,714	38,348,757	40,116,822
	Cargo Sorties Saved with Air Refueling	126	124	123	128	125
	Additional Tanker Sorties with Air Refueling	94	98	108	92	81
C-5 - KC-135	Rendezvous Point	34 26 43 N 50 4 0 W	33 16 56 N 52 24 12 W	31 14 9 N 54 56 45 W	28 11 57 N 54 3 17 W	38 37 54 N 42 38 27 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	120	122	124	121	124
	Tanker Sorties Needed	161	166	179	152	135
	Each Cargo Aricraft Cargo Load (lbs)	244,333	240,328	236,452	242,314	236,452
	Each Cargo Aricraft Initial Fuel Load (lbs)	143,781	148,126	151,925	146,686	152,548
	Total Fuel Savings With Air Refueling	38,205,177	36,200,332	32,772,126	39,315,999	40,884,435
	Cargo Sorties Saved with Air Refueling	130	128	126	129	126
	Additional Tanker Sorties with Air Refueling	161	166	179	152	135

Origin	Wheeler Sack AAF	44º 02' 44"	N	75º 43' 32"	W
Destination	Sierra Leone Lungi Intl. Airport	08º 37' 16"	N	13º 12' 39"	W

		Tanker Base				
		McGuire AFB	Semour Johnson AFB	McDill AFB	Roosevelt Roads	Lajes Field
C-17 - KC-10	Rendezvous Point	32 15 59 N	31 45 36 N	30 19 4 N	24 52 54 N	35 24 19 N
		45 18 30 W	48 3 55 W	50 39 29 W	45 41 45 W	37 6 53 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	182	187	191	174	173
	Tanker Sorties Needed	90	91	97	88	69
	Each Cargo Aricraft Cargo Load (lbs)	161,099	156,791	153,508	168,506	169,480
	Each Cargo Aricraft	141,199	145,092	148,958	133,994	133,020
	Total Fuel Savings With Air Refueling (lbs)	28,406,613	26,123,660	22,518,577	32,320,058	38,699,629
	Cargo Sorties Saved with Air Refueling	137	132	128	145	146
	Additional Tanker Sorties with Air Refueling	90	91	97	88	69
C-17 - KC-135	Rendezvous Point	30 38 43 N	30 20 17 N	29 29 54 N	24 52 54 N	35 24 19 N
		42 18 36 W	45 7 40 W	48 27 50 W	45 41 45 W	37 6 53 W
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	174	179	185	174	173
	Tanker Sorties Needed	158	159	163	140	112
	Each Cargo Aricraft Cargo Load (lbs)	168,506	163,799	158,486	168,506	169,480
	Each Cargo Aricraft Initial Fuel Load (lbs)	133,968	138,168	143,981	133,994	133,020
	Totaf Fuel Savings With Air Refueling (lbs)	30,366,956	28,220,920	24,931,671	33,694,385	39,263,228
	Cargo Sorties Saved with Air Refueling	145	140	134	145	146
	Additional Tanker Sorties with Air Refueling	158	159	163	140	112

Scenario 4

Origin		Ramstein AB				49º 26' 10"			N	07º 35' 02"		W
Destination		DR Congo				04º 23' 49"			S	15º 25' 35"		E
		Tanker Base										
		Ramstein				Aviano AB				Carthage IAP		
C-5 - KC-10	Rendezvous Point	34	41	33	N	32	50	10	N	32	42	32	N
		10	35	25	E	12	16	2	E	10	54	12	E
	Air Refueling Practicality	PRACTICAL				PRACTICAL				PRACTICAL		
	Cargo Sorties Needed	115				112				112		
	Tanker Sorties Needed	74				73				62		
	Each Cargo Aricraft Cargo Load (lbs)	254,957				261,786				261,786		
	Each Cargo Aricraft Initial Fuel Load (lbs)	133,573				127,127				125,186		
	Total Fuel Savings With Air Refueling (lbs)	19,058,857				20,801,485				24,418,248		
	Cargo Sorties Saved with Air Refueling	85				88				88		
	Additional Tanker Sorties with Air Refueling	74				73				62		
C-5 - KC-135	Rendezvous Point	32	42	33	N	32	49	49	N	32	42	32	N
		10	54	19	E	12	11	36	E	10	54	13	E
	Air Refueling Practicality	PRACTICAL				PRACTICAL				PRACTICAL		
	Cargo Sorties Needed	112				112				112		
	Tanker Sorties Needed	127				119				101		
	Each Cargo Aricraft Cargo Load (lbs)	261,786				261,786				261,786		
	Each Cargo Aricraft Initial Fuel Load (lbs)	126,815				126,169				127,205		
	Total Fuel Savings With Air Refueling (lbs)	20,001,658				21,547,577				24,747,295		
	Cargo Sorties Saved with Air Refueling	88				88				88		
	Additional Tanker Sorties with Air Refueling	127				119				101		

Origin	Ramstein AB	49º 26' 10"	N	07º 35' 02"	W
Destination	DR Congo	04º 23' 49"	S	15º 25' 35"	E

		Tanker Base		
		Ramstein	**Aviano AB**	**Carthage IAP**
C-17 - KC-10	**Rendezvous Point**	29 55 59 N	29 37 49 N	29 32 15 N
		11 19 25 E	12 20 25 E	11 22 48 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	173	172	172
	Tanker Sorties Needed	61	58	48
	Each Cargo Aricraft Cargo Load (lbs)	169,480	170,465	170,465
	Each Cargo Aricraft Initial Fuel	132,996	131,000	131,339
	Total Fuel Savings With Air Refueling (lbs)	13,741,965	15,231,039	18,262,971
	Cargo Sorties Saved with Air Refueling	84	85	85
	Additional Tanker Sorties with Air Refueling	61	58	48
C-17 - KC-135	**Rendezvous Point**	29 32 15 N	29 37 26 N	29 32 15 N
		11 22 52 E	12 15 47 E	11 22 48 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	172	172	172
	Tanker Sorties Needed	99	92	78
	Each Cargo Aricraft Cargo Load (lbs)	170,465	170,465	170,465
	Each Cargo Aricraft Initial Fuel Load (lbs)	132,001	131,995	132,034
	Total Fuel Savings With Air Refueling (lbs)	14,746,303	16,036,680	18,608,963
	Cargo Sorties Saved with Air Refueling	85	85	85
	Additional Tanker Sorties with Air Refueling	99	92	78

Scenario 5

Origin		Hickam AFB	21º 19' 30" N	157º 54' 27" W
Destination		Papua New Guinea	09º 27' 05" S	147º 13' 35" E
		Tanker Base		
		Hickam AFB	**Anderson AB**	**Kadena AB**
C-5 - KC-10	**Rendezvous Point**	13 21 16 N 174 30 58 W	10 30 0 N 167 54 8 E	10 37 13 N 160 6 43 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	123	142	159
	Tanker Sorties Needed	90	79	98
	Each Cargo Aricraft Cargo Load (lbs)	238,374	206,479	184,403
	Each Cargo Aricraft Initial Fuel Load (lbs)	150,596	182,521	204,597
	Total Fuel Savings With Air Refueling (lbs)	30,372,675	24,020,105	9,388,223
	Cargo Sorties Saved with Air Refueling	113	94	77
	Additional Tanker Sorties with Air Refueling	90	79	98
C-5 - KC-135	**Rendezvous Point**	12 10 46 N 176 40 3 W	10 30 41 N 168 55 25 E	10 52 26 N 162 7 39 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	119	140	154
	Tanker Sorties Needed	155	130	160
	Each Cargo Aricraft Cargo Load (lbs)	246,387	209,429	190,390
	Each Cargo Aricraft Initial Fuel Load (lbs)	142,396	179,571	198,610
	Total Fuel Savings With Air Refueling (lbs)	31,716,214	25,521,818	12,747,469
	Cargo Sorties Saved with Air Refueling	117	96	82
	Additional Tanker Sorties with Air Refueling	155	130	160

Origin	Hickam AFB	21° 19' 30"	N	157° 54' 27" W
Destination	Papua New Guinea	09° 27' 05"	S	147° 13' 35" E

		Tanker Base		
		Hickam AFB	**Anderson AB**	**Kadena AB**
C-17 - KC-10	**Rendezvous Point**	10 2 49 N	10 32 57 N	10 35 34 N
		179 32 48 E	168 0 43 E	160 7 16 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	181	183	205
	Tanker Sorties Needed	85	79	97
	Each Cargo Aricraft Cargo Load (lbs)	161,989	160,219	143,024
	Each Cargo Aricraft Initial Fuel Load (lbs)	140,195	142,281	159,476
	Total Fuel Savings With Air Refueling (lbs)	22,799,363	23,837,852	9,349,431
	Cargo Sorties Saved with Air Refueling	121	119	97
	Additional Tanker Sorties with Air Refueling	85	79	97
C-17 - KC-135	**Rendezvous Point**	8 41 59 N	10 50 29 N	11 1 33 N
		177 13 11 E	169 30 37 E	162 17 12 E
	Air Refueling Practicality	PRACTICAL	PRACTICAL	PRACTICAL
	Cargo Sorties Needed	174	179	198
	Tanker Sorties Needed	148	133	160
	Each Cargo Aricraft Cargo Load (lbs)	168,506	163,799	148,081
	Each Cargo Aricraft Initial Fuel Load (lbs)	133,852	138,701	154,419
	Total Fuel Savings With Air Refueling (lbs)	24,608,571	25,358,088	12,666,107
	Cargo Sorties Saved with Air Refueling	128	123	104
	Additional Tanker Sorties with Air Refueling	148	133	160

Appendix F: Quad Chart

Fuel Savings Opportunities from Air Refueling

1st Lt. Murat Toydas
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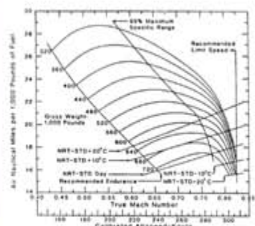
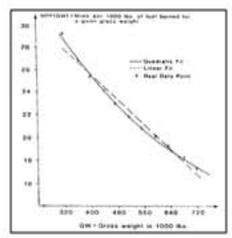
INTRODUCTION

Hence by exchanging take-off fuel for additional cargo and then later refueling while airborne, it is possible to reduce the total number of cargo aircraft sorties required to achieve a given air cargo movement. The potential savings are limited by the cargo aircraft's maximum takeoff weight limit and the distance between origin and destination, and the fuel consumed by the tanker aircraft.

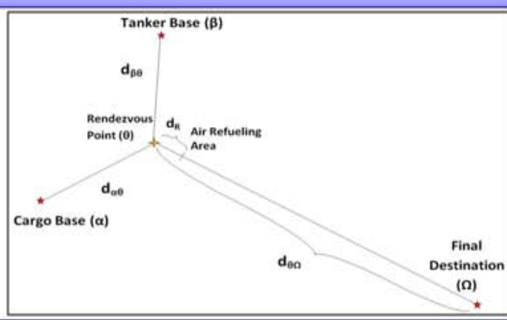
Research Question:
Can air refueling save fuel?

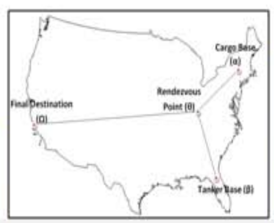
Sub Questions:
- What are the fuel burn functions of cargo and tanker aircraft
- What is the optimum air refueling point, number of cargo and tanker aircraft, initial cargo and fuel amount of each cargo aircraft to minimize the total fuel consumption for a given origin, destination, tanker base location and total cargo amount?
- What is the total fuel consumption for both "with air refueling" and "without air refueling option" for a given a given origin, destination, tanker base location and total cargo amount?





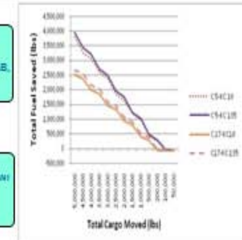
METHODOLOGY





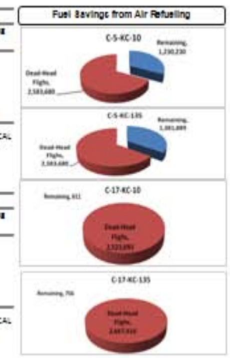
Two nonlinear models build that captures two tradeoffs:
- Tradeoff between initial fuel and freight loaded to cargo aircraft for a given origin, destination and amount of freight needed to be moved.
- Tradeoff between fuel saved by cutting cargo aircraft sorties versus additional tanker aircraft fuel consumption for the same inputs and tanker base location.

RESULTS



	C-5 - KC-10 Air Refueling Option	C-5 - KC-10 No Air Refueling Option	C-5 - KC-135 Air Refueling Option	C-5 - KC-135 No Air Refueling Option
Cargo Aircraft Sorties Needed	20	36	20	36
Tanker Aircraft Sorties Needed	15	0	21	0
Each Cargo Aircraft's Cargo Load (lbs)	250,000	142,719	250,000	142,719
Each Cargo Aircraft's Initial Fuel Load (lbs)	156,236	246,281	156,106	246,281
Total Fuel Consumption (lbs)	8,891,996	12,705,906	8,740,557	12,705,906
Conclusion	AIR REFUELING OPTION IS PRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	3,813,909		3,965,369	
Total Lifter Sorties Saved	16		16	
Additional Tanker Sorties Needed	15		21	

	C-17 - KC-10 Air Refueling Option	C-17 - KC-10 No Air Refueling Option	C-17 - KC-135 Air Refueling Option	C-17 - KC-135 No Air Refueling Option
Cargo Aircraft Sorties Needed	30	45	30	45
Tanker Aircraft Sorties Needed	11	0	18	0
Each Cargo Aircraft's Cargo Load (lbs)	166,667	111,174	166,667	111,174
Each Cargo Aircraft's Initial Fuel Load (lbs)	153,827	191,326	151,763	191,326
Total Fuel Consumption (lbs)	10,072,126	12,595,830	9,927,165	12,595,830
Conclusion	AIR REFUELING OPTION IS PRACTICAL		AIR REFUELING OPTION IS PRACTICAL	
Total Fuel Saved (lbs)	2,523,704		2,668,666	
Total Lifter Sorties Saved	15		15	
Additional Tanker Sorties Needed	11		18	



$$\text{Fuel Cost Ratio} = \frac{\text{Unit Cost of Fuel Offloaded in The Air}}{\text{Unit Cost of Fuel on The Ground}}$$

Breakeven Fuel Cost Ratio			
C-5-KC-10	C-5-KC-135	C-17-KC-10	C-17-KC-135
2.395	2.449	2.223	2.259

		C-5-KC-10	C-5-KC-135	C-17-KC-10	C-17-KC-135
"Air Refueling" Option	Cost of All Cargo Aircraft	$ 8,664,159	$ 8,664,159	$ 6,326,096	$ 6,326,096
	Cost of All Tanker Aircraft	$ 956,831	$ 1,254,568	$ 1,004,877	$ 1,361,289
	Total Cost	$ 9,620,971	$ 9,918,726	$ 7,330,973	$ 7,687,384
"No Air Refueling" Option	Total Cost	$ 15,632,030	$ 15,632,030	$ 9,489,144	$ 9,489,144
Cost Savings from Air Refueling		$ 6,011,059	$ 5,713,302	$ 2,158,171	$ 1,801,759

- Substantial fuel savings are possible from air refueling since it increases the payload and reduces the total number of airframe needed.
- The C-5 - KC-135 pair saves the highest amount of fuel from air refueling.
- The C-5 - KC-10 pair yields the highest cost savings from air refueling.
- More fuel and cost savings can be achieved if;
  - the tanker base is close to air refueling point,
  - larger amounts of total cargo are moved and,
  - the distance between origin and destination gets larger within the range of the cargo aircraft.

DEPARTMENT OF OPERATIONAL SCIENCES

Appendix G: Blue Dart

1st Lieutenant Murat Toydas, Student, AFIT

The United States of America is one of the largest fuel consumer countries in the world, at over 24% of total world oil production. In 2007, it used as much of oil as China, Japan, India, the Russian Federation, and Germany put together. Furthermore, the U.S. is highly dependent on foreign countries for fuel. It is importing roughly 58% of its petroleum products. Fuel is a critical strategic asset for military aviation operations, yet is increasingly expensive. In 2008, the USAF used 2.4 billion gallons of aviation fuel which costs $7.7 billion. Since the numbers are incredibly big, fuel conservation is a very hot USAF topic. One potential area that can conserve fuel is to use air refueling. Air refueling can save fuel by enabling a transport aircraft to depart with less fuel in exchange for additional cargo. However, it is not generally considered for distances flown within unrefueled range.

Air refueling is the process of transferring fuel from one aircraft (the tanker) to another (the receiver) during flight and it's a very useful capability. Major General Perry B. Griffith's comment that "No single innovation of recent times has contributed more to air power flexibility than the aerial tanker…" That is why during Operations Desert Shield and Desert Storm, approximately 400 tankers offloaded over 1.2 billion pounds of fuel to over 80,000 aircraft while flying over 30,000 sorties and logging over 140,000 hours of flight time. With air refueling, fighter aircraft can reach Saudi Arabia from the east coast over three times faster than by landing enroute to refuel. Additionally, air refueling supports many second order effects like enhancing flexibility, reducing operating locations, and increasing payload capacity.

Many studies have addressed aircraft fuel consumption in the hope of decreasing operating costs and extending range and capacity. In our study we investigated fuel savings opportunities from air refueling. As we mentioned before, while air refueling is always a significant option for enabling aircraft to reach destinations beyond their unrefueled range, it is seldom used to support aircraft flights within range. Hence by exchanging take-off fuel for additional cargo and then later refueling while airborne, it is possible to reduce the total number of cargo aircraft sorties required to achieve a given air

cargo movement. In this approach, cargo aircraft are loaded with maximum freight and minimum fuel and reserves to allow them to take off and fly to an air refueling area. There they meet with tanker aircraft and obtain the fuel to finish the mission. Fewer cargo aircraft sorties may thus be needed to move a given amount of freight. In this scenario, the tradeoff is between fuel saved by cutting cargo aircraft sorties versus the additional fuel burned by the tanker aircraft. In our research, we built a mathematical model to capture this tradeoff and possible savings for C-5, C-17 KC-10 and KC-135 aircraft. Additionally, we evaluated possible deployment scenarios with our model. Results showed that substantial fuel and dollar savings are possible. For example, for a scenario where we need to move 5 million lbs. of freight from McGuire Air Force Base to Ramstein Air Base in Germany we can save around 3.9 million lbs. of fuel and $6 million taxpayer money from air refueling. Higher savings is possible for greater amount of freights.

This research can be used immediately in the USAF heavy transport community to help planners make decisions about air transportation missions--particularly for deployment scenarios. Further, it can be used as a supplementary mission planning tool to the Computer Flight Planning Software/System (CFPS) and Advanced Computer Flight Planning System (ACFP) currently used by the USAF to plan aircraft missions and calculate flight fuel requirements. These efforts hopefully help to find more efficient uses of limited resources.

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Vita

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Fuel is a critical strategic asset for military aviation operations, yet is increasingly expensive. Air refueling offers both the opportunity to extend aircraft range and the potential to save fuel by enabling a transport aircraft to depart with less fuel in exchange for additional cargo. We evaluate the practicality of air refueling in terms of fuel savings versus distance and cargo quantity, by introducing two non-linear optimization models that examine the tradeoff between departure fuel weight and loaded cargo for given origin, destination, and tanker base positions and freight quantities to be moved. We use two numerical example scenarios to show that substantial fuel savings from air refueling are possible.

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